QUASI-STELLAR OBJECTS

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INTRODUCTION

The first quasi-stellar radio source was discovered in 1960, and during the past 6 years many papers, both observational and theoretical, have been published. Since this is the first review article on the subject, I have attempted to give a complete bibliography up to November, 1966 (somewhat earlier than this for overseas journals). A fuller account of the subject will be found in the book by Burbidge & Burbidge (50).

The name "quasi-stellar object" or "QSO" has been adopted here, to cover quasi-stellar radio sources (or quasars) and radio-quiet quasi-stellar sources (also called blue stellar objects, quasi-stellar galaxies, and interlopers in the literature).

Discovery

In 1960 the Owens Valley radio interferometer began producing accurate declination measurements of sources (167). In previous surveys the errors in declination had been substantially larger than those in right ascension. There became available then some sources with positions good to about $\pm 5''$ in both coordinates. Some of these were found to be of high radio surface brightness (small radio angular diameters), and with no obvious optical object (such as a galaxy) at the position. The first QSO to be discovered was 3C 48; within the small error rectangle around the radio position, the only optical object visible on a plate taken with the 200-inch Palomar telescope was a 16th mag. "star" with a faint wisp of nebulosity attached. The first optical observations were reported at the 107th A.A.S. meeting in

December, 1960 (177). Sandage, followed by a number of astronomers, both at Palomar and elsewhere, obtained spectra of 3C 48 and saw broad emission lines at wavelengths that did not correspond with features normally seen in emission-line stars.

A radio position of 3C 273 accurate to better than $1''$ was measured by means of a lunar occultation of the object, observed with the Parkes 210-ft. radio telescope by Hazard, Mackey, & Shimmins (103). As in 3C 48, the brightness temperature was large, the source having a small angular diameter. The source had two components, A and B. Hazard et al. noted that the position of component B agreed with that of a 13th magnitude star, and Schmidt (192) obtained spectra of this and noted that, like 3C 48, it had some nebulosity associated with it, in the form of a faint jet extending from the stellar object in exactly the direction of the separation between the two radio components, with component A lying at the end of the optical jet. Schmidt found broad emission lines in 3C 273 and identified them with Balmer hydrogen lines and Mg II λ2798, shifted to longer wavelengths by an amount $z = \Delta\lambda/\lambda_o = 0.158$. Following this, Greenstein and Matthews (96) were able to identify the spectroscopic features in 3C 48 and obtained $z = 0.367$ for it.

General Properties

Schmidt (193) has described the optical properties of the QSO's as follows:

(1) they are star-like objects identified with radio sources;

(2) they are variable in light;

(3) they have a large ultraviolet flux of radiation;

(4) there are broad emission lines in the spectra;

(5) the spectrum lines have large redshifts.

Bearing in mind the discoveries made since these definitions were given, we replace (1) by (1a): star-like objects <u>often</u> identified with radio sources, and (4) by (4a): broad emission lines in the spectra, with absorption lines sometimes present.

Regarding property (3), Sandage's photometry of 3C 48 in 1960 (177, 142) gave V = 16.06, B-V = 0.38, U-B = -0.61, i.e. 3C 48 lies well above the locus of main-sequence stars in the two-color diagram, up in the region where some white dwarfs, old novae, and related highly evolved stars lie, and this has been found to be a very general property of QSO's.

IDENTIFICATION OF QSO'S

Quasi-Stellar Radio Sources

Of the properties of 3C 48 and 3C 273 - small radio diameter, star-like optical object, ultraviolet excess in the optical radiation, and peculiar emission-line spectrum, it is the ultraviolet excess which has proved particularly valuable in making identifications of QSO's, once accurate radio positions are available. Objects identified in the same period were 3C 196 and 3C 286 (142).

As is often the case in a period of rapid discoveries it is not possible to put the advances in chronological order by directly using the dates on references. Matthews and Sandage (142) gave the fundamental optical identifications and data on 3C 48, 196 and 286 in a paper completed in 1962. At that time it was generally believed that these objects were likely to be galactic stars. The discovery of 3C 273 came while their paper was in press and thus they added a note in proof concerning the extragalactic nature of these objects. Like 3C 48 and 273, 3C 196 and 286 have small radio diameters and in each case the only object within the error rectangle around the radio position was a 17th magnitude star. A wisp of nebulosity was seen associated with the stellar object identified with 3C 196 but none was found in the case of 3C 286. The U, B, V colors were measured and the objects lie in the same region as 3C 48 in the two color diagram.

A list of positions of optical objects found close to 42 radio sources of fairly small angular diameter and accurate radio positions was published by Griffin (98). In addition to 3C 48, 3C 196, and 3C 286, this list included stellar objects at the positions of 3C 147 and 3C 298, which were later proved to be QSO's. No wisps of associated nebulosity were found around these objects, and in fact this feature is absent in the majority of QSO's now known and has not proved to be of use in making identifications after the first few cases. The U, B, V colors of 3C 147 and 3C 298 were not measured at that time; Griffin's identifications were made solely on the basis of a star-like image being the only object seen within the error rectangle around an accurate radio position.

Hazard, Mackey, & Nicholson (102) obtained very accurate radio positions of more sources by the lunar occultation method, and suggested optical identifications for them; of these, 3C 245 and MSH 14-121 were later proved, on the basis of photometry and spectroscopy, to be QSO's as Hazard et al. had suggested.

Since the first QSO's were found to have ultraviolet excesses, Ryle & Sandage made a search for identifications at good radio positions by taking two successive direct exposures on the same plate, through a blue and an ultraviolet filter, and picking out stellar images that were stronger on the ultraviolet exposure. Longair (130) had searched the fields around 88 radio sources of small angular diameter with good radio positions (63) and found 4 possible QSO's. Ryle & Sandage (175) certainly identified 3C 9, 216, and 245 as QSO's; 3C 9 and 245 had been suggested by Longair. Next Schmidt & Matthews (196) identified 3C 47 with a stellar object appearing rather blue from comparison of the red and blue Palomar Sky Survey prints. It was confirmed as a QSO by its spectrum, as was also 3C 147, identified by Griffin (98).

Adgie (1) identified 3C 254, using a radio position determined with the Royal Radar Establishment interferometer at Malvern and Griffin's measures of positions of optical objects in the fields of radio sources. Sandage & Wyndham (188) identified 11 more QSO's, by means of positional agreement between a stellar object and a radio source together with either two-color photographic plates showing that the stellar object had an ultraviolet excess, or the observation that the stellar object appeared stronger on the blue Palomar Atlas plate than on the red.

The number of identified or possible QSO's then rapidly increased (Wyndham (232,233), Sandage, Véron, & Wyndham (186)). At this time, new catalogues of radio sources from Parkes, Cambridge (the 4C), and NRAO were becoming available. Bolton et al. have identified many possible QSO's by comparing the Parkes radio positions with the positions of nearby blue stellar objects on the Palomar Sky Survey prints (26,27,29,30)(31,64,79). Between -20° and +20° some 80 possible QSO's have been listed; optical confirmation in the form of U, B, V photometry and spectroscopic observations has been made for at least a third of these (27, 33, 34). QSO's in the first sections of the 4C catalogue to appear have been identified by Wyndham (234), Scheuer & Wills (191), and Wills (230).

Radio-Quiet QSO's

During the course of searches for identifications by blue and ultraviolet exposures, both Sandage and Lynds (with the Kitt Peak 84-inch telescope) sometimes found ultraviolet objects that did not lie close to the radio positions. Sandage found about 3 such objects per square degree to a limiting magnitude $B \approx 18^{m}.5$. These objects are of the same type as those found in previous surveys in high galactic latitudes undertaken by Humason, Zwicky, Luyten, Iriarte, Chavira, Haro, Feige, and others. The relevant references are listed by Sandage (179). These previous surveys had yielded a frequency of about 4 ultraviolet objects per square degree to $B \approx 19^{m}.0$.

Sandage found that in a two-color plot (U-B against B-V), the objects divided into two groups, those brighter and those fainter than $V = 14^{m}.50$. The brighter objects lay mostly in the region where lie normal fairly high-temperature stars, with some in the region of metal-deficient old halo population stars. Very few lay in the region where the QSO's lie. But for $V > 14^{m}.50$, while some were clearly normal high-temperature or metal-deficient stars, the majority lay well above the normal sequence, in the region where QSO's lie. In a plot of log N(m) against m, where N(m) is the number of objects brighter than magnitude m, Sandage found a change of slope at about 15th magnitude, suggesting a change in the type of objects being sampled at this point, and concluded that the majority of the fainter blue stellar objects are extragalactic, with large redshifts, and in fact are QSO's that are radio-quiet down to the limits set by existing radio source catalogues. Of six objects whose spectra were taken, one was a galactic star, two had continuous spectra with no emission or absorption features, and three were extragalactic. Of these, one had a non-stellar image and a small redshift, but two had completely stellar images, one with a spectrum indistinguishable from the radio QSO's and a large redshift; this was called BSO 1. The other had a similar kind of spectrum and a smaller redshift; it is Ton 256 (Ton = Tonanzintla).

Sandage concluded that virtually all high latitude blue stellar objects fainter than 15th magnitude are QSO's that are radio-quiet down to limits set by the existing catalogues. Thus, with a frequency of 4 per square degree, these would be 500 times more numerous, spatially, than the QSO's identified with radio sources.

The validity of this conclusion hinges on Sandage's interpretation of the plot of log N(m) against m, and alternative interpretations were given almost immediately by Kinman (125) and by Lynds & Villere (138). With more recent determinations of the density of horizontal-branch type stars in the halo of our Galaxy as a function of distance from the plane, and new estimates of the frequency of white dwarfs, Kinman found that the observed log N(m) vs m plot could be well represented by a combination of these. Lynds and Villere reached essentially the same conclusion. Thus the bulk of the objects in question are probably galactic stars - white dwarfs mostly, evolved hot sub-dwarfs, and halo stars of the horizontal-branch type. This conclusion was supported by a random sampling of spectra of 12 stars of about 16th apparent magnitude by Kinman (125); 7 were found to be white dwarfs, 4 were horizontal-branch stars, and 1 was a hot sub-dwarf star.

There are undoubtedly a number of compact blue galaxies among the blue stellar objects, as discovered by Humason & Zwicky (117), Zwicky (237), and Haro (100). Sandage & Luyten (183) have isolated a larger sample of possible QSO's, using colors and zero proper motion as criteria. Some of these objects have been seen to show light variations. Van den Bergh (223) has also prepared a list of faint blue objects with excess ultraviolet radiation, and some vary in light.

At present it is difficult to estimate the true frequency of QSO's among the fainter blue stellar objects in the high latitude surveys. Kinman estimated that it was 20% or less of Sandage's estimate. However, even if Sandage's numbers were reduced by a factor 10, these QSO's would still be about 50 times more numerous spatially than the QSO's identified with radio sources.

Table I lists known and probable QSO's with coordinates, photometry, and redshifts where measured. An object lettered PHL is from the Palomar-Haro-Luyten catalogue of blue stellar objects (101), and Ton denotes the various lists by Chavira & Iriarte (118, 60, 61). Not all suggested identifications are given in Table I, only those with some supporting evidence besides position coincidence.

LINE SPECTRA OF QUASI-STELLAR OBJECTS

The first spectrogram of 3C 48 was obtained in 1960 by Sandage. Early spectroscopic work was carried out by Greenstein, Münch and others on this object. Following his discovery of the redshift of 3C 273, Schmidt was largely responsible for all of the spectroscopic observations of the QSO's until 1964 when others entered the field, namely, Lynds and colleagues at Kitt Peak National Observatory with an image tube spectrograph, Burbidge & Kinman at Lick with a conventional spectrograph and more recently with an image tube spectrograph, Dibai & Pronik with an image tube spectrograph at the Crimean station of the Sternberg Institute, Andrillat & Andrillat at Haute Provence, Ford & Rubin with an image tube spectrograph at Lowell and Kitt Peak, and Hiltner and colleagues with an image tube spectrograph at McDonald.

Line Identifications

The identification by Schmidt (192) of 4 broad emission lines in the brightest QSO, 3C 273, as the Balmer lines Hβ-Hε with a redshift z = 0.158, provided the break-through in understanding the line spectra of these objects by demonstrating that considerable redshifts are present. From the redshift given by the Balmer lines, Schmidt identified a broad emission feature as a blend of the Mg II doublet $\lambda\lambda$ 2796, 2803, which had hitherto only been seen in solar spectra taken outside the Earth's atmosphere. Oke (155) detected Hα in 3C 273.

The λ2798 feature was then identified by Greenstein & Matthews (96) in 3C 48, and this together with several other emission lines, gave a larger redshift for this object. A detailed analysis of 3C 48 and 3C 273 was then carried out by Greenstein & Schmidt (97).

The identification of 17th and 18th magnitude stellar objects with radio sources, in conjunction with the redshifts found for 3C 273 and 3C 48, and, later, for 3C 47 and 3C 147 by Schmidt & Matthews (196), suggested that objects with really large redshifts might be found (38). In these spectra the ultraviolet wavelength region normally inaccessible from ground-based instruments, and therefore at that time unobserved except in the sun, could be expected to be shifted into the visible region, posing a considerable problem in identifying the lines. The lines found in 3C 48 and 3C 273 (all emission lines, and all very broad) besides the Balmer lines and Mg II, are due to [O II], [O III], [Ne III], [Ne V]. These are the sort of features to be expected in hot gaseous nebulae with physical conditions similar to those of planetary nebulae, in radio galaxies like Cygnus A, and in nuclei of Seyfert galaxies. Osterbrock (158) had prepared a list of emission lines to be expected in the ultraviolet spectra of planetary nebulae, with computed relative intensities. Schmidt (194) compiled a search list of emission lines with which he identified emission features in 5 more QSO's, all of which proved to have very large redshifts, running up to z = 2.012 in 3C 9, in which, for the first time, Lyman α was seen as a strong emission feature.

A search list similar to Schmidt's is given in (50).

The four strongest emission lines in the wavelength range extending shortward from about 5000Å are Ly-α, C IV λ1549, C III] λ1909, and Mg II λ2798. Apart from λ1909, these are resonance transitions involving the ground level of the ion in question. If a spectrum shows only two emission lines, the ratio of whose wavelengths agrees with any of the ratios of rest wavelengths from these four lines, then it is relatively certain that they are the correct identifications. Although λ1909 and λ1549 give a ratio fairly near that of [Ne V] λ3426 and Mg II λ2798, the presence or absence of other lines at predicted wavelengths usually settles the question.

Table II lists in order of increasing z all the redshifts determined to date. The details of the emission features detected in the spectrum of each object, with approximate strengths and widths, were compiled by Burbidge et al. (51) and a later version is given in (50). The lines found belong to ions with a wide range of ionization potentials, in the light elements that are most abundant in the sun and stars of the solar neighborhood. The elements H, He, C, N, O, Ne, Mg, Si, S, and Ar are all represented; of the elements heavier than Ar, the only suggested identification is a coronal line of Fe at whose wavelength Wampler at Lick and Oke at Palomar have detected a weak feature with their spectrum scanners.

Absorption Lines

The first QSO's for which redshifts were determined all showed only emission lines in their spectra, and consequently the first models for explaining the line spectra did not include any provision for discussing absorption lines. It is now clear, however, that absorption lines are not uncommon in the spectra of QSO's.

The first recorded observation of absorption lines was in Schmidt's spectra of the radio-quiet QSO known as BSO 1 (179), in which the broad emission of C IV λ1549 is bisected by a sharp absorption. Absorption components in the short-wavelength wing of both Ly-α and C IV λ1549 were found in PHL 938, another radio-quiet QSO, by Kinman (126).

3C 191 was then found to show a large number of sharp absorption lines in its spectrum (45,214), as well as some of the usual broad emission lines. These absorptions are almost all from the ground state of the relevant ions, and include Ly-α and C IV λ1549. One of the absorption-line identifications by Burbidge et al. (45) and Stockton & Lynds (214) in 3C 191, namely N V λ1240.1, was questioned by Bahcall (14), who believed it might be due instead to a blend of Mg II λλ1239.9, 1240.4. Burbidge & Lynds (44), however, replied that Stockton's Kitt Peak spectrogram of 3C 191 resolves the line into fine-structure components at the right wavelengths for N V; moreover, the Mg II lines are the second member of the principal series in Mg II, and the transition probability can be only a few percent of that of Mg II λ2798.

A strong absorption component appears in the short wavelength wing of Ly-α in PKS 1116+12 on a spectrum taken by Lynds & Stockton (136), about 26Å from the center of the Ly-α emission. It was apparently not seen by Schmidt (195) on his spectra of PKS 1116+12, but Bahcall, Peterson, & Schmidt (15) detected two other absorptions, probably Ly-α and C IV, at a redshift corresponding to some 17,000 km/sec less than the respective emission-line centers. Lynds & Stockton saw the one corresponding to Ly-α, but not the other.

Ford & Rubin (87) found redshifted Ca II H and K absorption lines in 3C 263; their redshifts agreed with that obtained from the emission lines. On the other hand, Lynds did not see the Ca II absorption lines in his spectra of 3C 263. Possibly absorption lines can be variable on a short time scale in the spectra of QSO's.

Other QSO's for which there is published evidence for absorption lines are 3C 270.1 (in the shortward wing of C IV λ1549) (195) and PKS 1510-08 (in the shortward wing of Mg II λ2798) (43).

The absorption lines described above are mostly presumed to arise in gas associated with the QSO and not in the intergalactic medium. Bahcall & Salpeter (16, 17) considered the possibility that resonance lines due to atoms and ions of the most common elements might be produced by gas in clusters of galaxies lying between the QSO and observer; in cases where the ground level had fine structure, only absorptions from the zero energy state would be expected. In 3C 191, however, there appears to be normal occupancy of all the fine-structure states in the ground levels of Si II and N V. Bahcall, Peterson, & Schmidt (15) suggested the absorptions in PKS 1116+12 might be intergalactic.

The Nature Of The Redshifts

There are two mechanisms which are known to cause spectral line shifts, line-of-sight velocities and strong gravitational fields. Döppler shifts can be either redward or blueward, but outside the local group of galaxies in the expanding universe we only see receding objects, and hence redshifts.

Gravitational redshifts. - Greenstein & Schmidt (97) discussed the possibility that the redshifts of 3C 48 and 3C 273 might be gravitational, arising in either (a) a collapsed star in our Galaxy or (b) a collapsed mass of galactic size outside our Galaxy. In either case, the gradient of gravitational potential across the region where the spectrum lines arise will produce a broadening of the lines. They took the observed line widths as limiting the size of this gradient. For a collapsed star of solar mass, which must not be very nearby because of the absence of measured proper motions, this sets an upper limit on the linear thickness of the shell and hence a lower limit to the density of gas in the shell (since a determined number of emitting atoms are required to give the observed emission line fluxes). The limiting density of $N_e \geq 6 \times 10^{18}$ cm^{-3} for 3C 273 was incompatible with the presence of the forbidden line [O III] λ5007 in 3C 273.

If 3C 273 were a massive object, outside our Galaxy but not at a large distance, Greenstein & Schmidt obtained limits by the condition that the mass must not be great enough nor the distance small enough to produce detectable perturbations on stellar motions, i.e. this effect must be less than 10% of the gravitational acceleration of the whole Galaxy. Taking $Ne \sim 10^7$ cm^{-3}, this gave limits on the distance d and mass M as follows:

$d \geq 2{,}500$ pc, $M/M_\odot \geq 7 \times 10^8$ (3C 273)

$d \geq 25{,}000$ pc, $M/M_\odot \geq 7 \times 10^{10}$ (3C 48) .

Thus collapsed massive extragalactic objects on this scale could account for the observed redshifts in these two objects, but the conditions are rather stringent. For objects with $z \simeq 2$, the above limits will be changed, but not by a large factor.

From the theoretical standpoint the situation is not clear. The question has been considered by Buchdahl (36, 37) and Bondi (35), and it appears that for a sphere in static equilibrium, $z < 2$. It has also been suggested that the redshifts may be gravitational in origin and arise when matter is infalling onto a collapsed object, or in an object in gravitational collapse. We note that emission-line redshifts exceeding $z = 2$, although not by a large amount, have been found, but absorption-line redshifts appear to be limited to $z < 2$.

Doppler shifts. - Most workers have generally agreed that the redshifts must be due to the motion of the QSO's relative to the observer, and most have gone further and assumed that the redshifts are cosmological in origin and are due to the expansion of the universe. Alternatively it has been suggested that the redshifts are Doppler shifts due to the translational motion of a local object. Terrell (221,222) argued that the objects were ejected from our Galaxy at relativistic speeds. Hoyle & Burbidge (107) considered the possibility that the objects have been ejected from comparatively nearby radio galaxies in which violent explosions have occurred. These theories will be discussed below.

Other causes. - Arp (10, 11) has argued that the redshifts are "non-velocity" shifts, but has not suggested any previously neglected physical mechanism. *

Interpretation Of The Line Spectra

Despite the fact that it is not yet possible to study the whole spectral region of any single QSO, from putting together the observations of many QSO's with various redshifts, it is clear that there are differences in the relative intensities of emission lines and in the lines to continuum from one object to another (50, 51, 54). The task of constructing a model of the line-producing region can therefore be applied either to one particular QSO, or to some generalized "average" QSO. Since the emission lines are of the sort seen in gaseous nebulae, the standard methods of analyzing these can be applied.

This type of analysis was applied by Greenstein & Schmidt (97) to 3C 273 and 3C 48, and by Shklovsky (206) and Dibai & Pronik (76) to a spectroscopic study of 3C 273 made with the telescope in Crimea. When spectroscopic observations became available for other objects, Osterbrock & Parker (159)

* Boccaletti et al. (24) have suggested that the observed wavelengths are produced in transitions in atoms and ions containing one or two quarks, but the calculated wavelengths do not agree well with the observed ones.

used them to derive the physical conditions in an average or composite of nine QSO's.

Greenstein and Schmidt assumed that the abundances of the elements in 3C 273 and 3C 48 are the same as the average Population I abundances of gaseous nebulae and young stars in the solar neighborhood in our Galaxy, and estimated $T_e = 16,800°K$ for the electron temperature. Then they calculated the relative intensities of the lines that were measured, for various values of the electron density N_e, and found the value which gave the best fit to the observations. Somewhat ambiguous estimates of the electron densities resulted (in that the same calculations applied to planetary nebulae yielded relative intensities that needed correction by arbitrary factors to agree with the observations, and the same "correction factors" were applied to the QSO's). The results are as follows:

$N_e = 3 \times 10^4 \text{ cm}^{-3}$ for 3C 48

$N_e = 3 \times 10^6 \text{ cm}^{-3}$ for 3C 273,

with uncertainty factors of about an order of magnitude either way.

Dibai & Pronik derived a higher value for the electron density in 3C 273, i.e., $N_e \approx 10^7 \text{ cm}^{-3}$, with a temperature $T_e \approx 10,000° - 15,000°$. Shklovsky pointed out that the smallness of the Balmer discontinuity in the continuous spectrum of 3C 273 suggests that T_e is at least as high as 20,000°, while the strength of the Hβ emission line relative to the continuum shows that $T_e < 60,000°$. Thus Shklovsky's value of $T_e \approx 30,000°$ seems a good choice. The absence of [O II] 3727 and [Ne V] lines in 3C 273 shows that N_e must be higher in 3C 273 than in 3C 48; later observations have indicated that 3C 48 is more typical of most QSO's than is 3C 273.

Cameron (56) estimated a still higher value for N_e in 3C 273, namely $2 \times 10^8 \text{ cm}^{-3}$, but Greenstein & Schmidt thought an upper limit to the acceptable electron density in this object would be 3×10^{7} cm^{-3}. $N_e = 10^{7}$ cm^{-3} is probably the best estimate. Osterbrock & Parker for their composite average QSO found a good match with the observations for $T_e = 15{,}000^{\circ}$ and $N_e = 3 \times 10^{6}$ cm^{-3}, for an assumed level of ionization (again assuming normal or Population I relative element abundances).

The fact that the studies just described yield relative intensities that match the measures reasonably well shows that the abundances must be similar to those found in young Population I stars and gaseous nebulae in the solar neighborhood. If the QSO's are indeed extremely distant objects dating back billions of years in time in an evolving universe, this is an extremely surprising result; Shklovsky (206) was the first to draw attention to this. Osterbrock & Parker (159) found that the only possible exception to this is He; they predicted that the line of He II λ1640 should be of comparable intensity with C IV λ1549, while actually it is weaker in all cases and in some QSO's it has not been seen. They suggested that helium might be less abundant, with respect to hydrogen and the heavier elements, in QSO's than in the "normal" abundance distribution.

Burbidge et al. (51), however, pointed out that an ionization equilibrium for QSO's had not been calculated; a distribution among the various ionization stages which seemed reasonable had been assumed, with He taken to be 50% doubly ionized. This might not be the case; there might well be less doubly ionized He than this.

<u>Dimensions and mass of region giving emission lines</u>. - If the redshifts are of cosmological origin, the luminosity-distances of QSO's may be derived from them for any chosen cosmological model. Greenstein & Schmidt used a model with the deceleration parameter $q_o = 0$ and from the equivalent widths of Hβ in 3C 48 and 3C 273 obtained Hβ luminosities of 6.4×10^{42} erg/sec

(3C 48) and 8.8 x 10^{43} erg/sec (3C 273). Shklovsky, using the measures of Dibai & Pronik, found the Hβ flux in 3C 273 to be 8 x 10^{43} erg/sec.

From these values, with T_e and N_e determined, using the hydrogen recombination formula, Greenstein & Schmidt obtained values for the radius R, and mass M_H, of the hydrogen emitting region, as follows:

3C 48: $R = 11$ pc, $M_H/M_\odot \approx 5 \times 10^6$

3C 273: $R = 1.2$ pc, $M_H/M_\odot = 6 \times 10^5$.

If the redshifts are not of cosmological origin, and if the objects are at about 10 Mpc distance, as has been suggested (107), then the values will be much reduced, as follows:

3C 48: $R = 0.48$ pc, $M_H/M_\odot = 410$

3C 273: $R = 0.092$ pc, $M_H/M_\odot = 270$.

<u>Widths of the emission lines</u>. - Emission lines in 3C 48 and 3C 273 are some 20-30Å wide. Still broader lines have been found in other QSO's; sometimes the observed widths are as great as 100Å (see 51).

To obtain widths as emitted in the rest frame at the source, these should be divided by (1+z). In general the resonance lines Ly-α, C IV λ1549, and Mg II λ2798 are the broadest, and the forbidden lines are narrowest. In PKS 1217+02 Lynds (51) found that the forbidden lines of [O III] at λ4959 and λ5007 are much narrower than [O III] λ4363, which has a higher excitation for the upper level of the transition. Such effects suggest stratification in the region producing the spectral lines. The absorption lines, when present, are characteristically very much narrower than the emission lines, again suggesting stratification. In 3C 191, Stockton's spectrum (214) shows that those lines which are not blended have about the same width as the weaker comparison lines, or about 8Å between half-intensity points. This sets an upper limit of about 3Å to their width at the source.

The emission line widths were first assumed to be due to mass motions of the gas, of the order of thousands of km/sec (97). These greatly exceed the velocities of escape set by the masses of the hydrogen emission region which are only ~ 100 km/sec. If the gas were free to escape, the time scales would be only $10^3 - 10^4$ years. Therefore the gas should be anchored by the gravitational attraction of a large mass at the center of the gas cloud, and to do this, a mass of about $10^9 M_\odot$ is required (97).

In one of the physical models that have been proposed for QSO's (see later), Colgate & Cameron (69) suggested that supernova explosions might be occurring with great frequency in the centers of dense star clusters. Then the emission lines would come from shells of gas ejected from the supernovae with characteristic speeds of thousands of kilometers per second; these shells would collide with each other and with quiescent gas in the cluster, and emission lines very much broadened by Doppler shifts would be produced.

Another possible broadening agent is electron scattering (51). That electron scattering might be very important in QSO's was realized by Shklovsky (206). In 3C 273, with the dimensions of the hydrogen emission region determined for a cosmological distance, the optical depth in electron scattering, τ_e, must be about 10. This holds for a thick spherical shell of radius 1.2 pc. But there is presumed to be a small central object inside this, which is giving the continuum radiation, and this radiation varies. An arbitrarily short pulse of radiation produced in the center would take 10 - 20 years to escape through such an electron-scattering region, because the velocity of diffusion of the quanta would be c/τ_e. To avoid this difficulty, we should have $\tau_e \leq 1$, and to do this with the physical parameters deduced for 3C 273, the hydrogen emission region must be spread out over a much larger dimension. Shklovsky suggested it might be in a comparatively thin closed spherical shell of much larger radius.

Schmidt (193) suggested that the hydrogen emission region might be in the form of filaments with an electron density N_e embedded in a large region of much lower density. Again, the light from the central object would only cross a few such small filaments and the electron scattering could be kept low.

Shklovsky also considered a non-uniform distribution of the line-emitting gas, but rejected this possibility because a non-uniform distribution of gas would not lead to complete absorption of the ultraviolet quanta from the energy source. Even if τ_e is considerably less than 10, there can be considerable broadening of the emission lines by electron scattering; this was considered quantitatively by Burbidge et al. (51).

The widest lines that are seen are Ly-α, C IV λ1549, and Mg II λ2798. In the case of permitted resonance lines quanta are emitted and reabsorbed in sequence until electron scattering out of the line center takes place. The opacity within about $\pm$3A from the line center is large and not until electron scattering takes the quanta sufficiently off resonance can they escape. Using the computations of electron scattering profiles by Münch they found that, even with small optical depths along a direct linear path through the gas, a width of about 20Å is obtained for an electron temperature of 10,000°K, $\sim$ 30Å for $T_e \approx$ 30,000°K, and $\sim$ 50Å for $T_e \approx$ 100,000°K. For really strong lines the widths can be nearly double this.

In the case of forbidden lines the ion which gives rise to the transition does not supply a high opacity near the central frequency. To broaden a forbidden line appreciably, τ_e must be $\sim$ 1. Again using the results of Münch, they found for τ_e = 0.8 a width of about 40Å at $T_e \approx$ 30,000°K, and about 60Å at T_e = 100,000°K. In the cases in which narrow forbidden lines are seen, τ_e must be small.

The early line identifications, including [O II] and [Ne V] in 3C 48, showed that a wide range of ionization potential is encompassed, and Shklovsky (206) pointed out that the line-producing region should be stratified, with [O II], for example, coming from a different layer from that giving rise to [Ne V]. According to Osterbrock & Parker (159), however, a wide range of ionization could result from photoionization by thermal radiation from a very hot super-massive star or by ultraviolet synchrotron radiation, since both have a great abundance of high-energy photons.

However, the great strength of the Mg II λ2798 emission line and the narrow absorption lines in several QSO's provide more cogent reasons for considering a stratified model, and Burbidge et al. (51) proposed such a model with three distinct zones, I, optically thick to quanta with $h\nu > 13.60$ eV, II, optically thick to quanta with $h\nu > 54.40$ eV, and III, optically thick to quanta with $h\nu > 24.58$ eV.

Zone I is necessary to explain the presence of the Mg II emission. The ionization potential of Mg^+ is only 15.03 eV and this ion can exist in appreciable abundance only in an H I region. Zone II will be responsible for most of the emission lines, including C IV, He II, O III, O IV, Ne III, Ar IV, while the absorption lines, C II, C III, and O II can arise in Zone III. In Zone III, all Mg will be doubly ionized. Zone I was suggested to lie innermost (to account for the breadth of Mg II λ2798 and lack of absorption in this line), and Zone III on the outside (to explain narrow absorption lines and a tendency for [O II] λ3727 to be narrower than other emission lines).

A further reason for placing Zone I on the inside is the absence of [O I] λλ 6300, 6363 in 3C 273. Andrillat & Andrillat (9) did not see these features on their infrared spectra, yet they are commonly seen in the spectra of the nuclei of Seyfert galaxies. If the H I region is innermost, then the electron density here may be sufficient to cause considerable collisional de-excitation of the upper level of the [O I] lines, and these lines will be suppressed.

An interesting question is whether higher Lyman lines - Ly-β and Ly-γ - will be visible in QSO's with z appreciably greater than 2. The usual analysis of ultraviolet radiation transfer in gaseous nebulae postulates that all the higher Lyman lines will be transformed by repeated absorptions and cascade re-emissions into lines of the Balmer, Paschen, etc. series and Ly-α. Bahcall (13) showed, however, that this will not be the case; there will actually be appreciable emission in Ly-β and Ly-γ due to leakage from the surface layers of the line-producing region.

CONTINUOUS ENERGY DISTRIBUTION

The Observations

In the optical wavelength region, knowledge of the continuous energy distribution comes from measurements with spectrum scanners for a few objects and U, B, V measures of a considerable number of objects. 3C 273 has been measured by scanner by Oke (156, 157), as have also 3C 9, 48, 245, 286, 446, and CTA 102. 3C 9 has been measured by scanner by Field, Solomon, & Wampler (86). The U, B, V measures collected in Table I are from Matthews & Sandage (142), Ryle & Sandage (175), Sandage (179), Sandage & Wyndham (188), Sandage & Veron (185), Bolton et al. (34), Bolton & Kinman (33), and Sandage (180).

In order to compare scanner measures of objects with different red-shifts, the observed absolute-energy distribution has to be shifted back to the wavelength in a system at rest with respect to the observer. The formula for doing this is given by Oke (157); it depends on the cosmological model adopted, and its form for a deceleration parameter $q_o = +1$ is the same as for local objects moving at relativistic speeds. Oke adopted the $q_o = +1$ model.

For 3C 273 the observations have been extended into the infrared by Johnson (120) and by Johnson & Low (121) and both 3C 273 and 3C 279 have been measured in the millimeter region by Low (132) and by Epstein (81).

Radio fluxes are given in the various radio source catalogues: MSH (145, 146, 147); 3C (78, 23); Parkes (32, 166, 72, 205) 4C (165, 95).

Form of the Continuous Energy Spectrum

Only for 3C 273 is a spectrum available covering almost the whole observable frequency range, from 85 M_c to 10^{15} cps, with an upper limit to an x-ray flux at 10^{18} cps; a plot of this has been given by Stein (213). Oke (157) compared his scanner measures with the computed hydrogen spectra at $T_e = 14,000°$ and $160,000°$ and showed that neither fitted the observations; the Balmer discontinuity at $T_e = 14,000°$ was too large (only a very small jump is observed), and the observed continuium rises into the infrared, suggesting that synchrotron radiation is becoming important here. A similar comparison of the observations with computed fluxes at these two temperatures was made by Hoyle, Burbidge, & Sargent (110), with the far infrared measurement added; the steep rise noted by Oke continues as the wavelength increases. Such a steep rise must represent flux emitted by a non-thermal process, either synchrotron emission or emission by the inverse Compton process. In either case a flux of high-energy electrons must be present; in the first case a magnetic field must be present, and in the second there must be an intense radiation field of low-energy quanta. In other QSO's (see (157)) it is conceivable that the continuum could arise from a very hot gas, $T \sim 10^5 - 5 \times 10^5$ degrees.

Matthews & Sandage (142) discussed the form of the energy spectrum in the optical region that would give the observed U-B, B-V colors of QSO's, and gave formulae by means of which the colors that would be given by any theoretical spectrum can be computed. They showed that the correct colors would be obtained for energy distributions both with an exponential dependence on frequency and with a power law dependence of the form $F(\nu) \propto \nu^{-n}$, with n lying in the range 0 to 2.

The U, B, V measures necessarily include the flux put out in any emission lines occurring in the band-pass of the filter together with the pure continuum radiation admitted through each filter. Yet, aside from this complication, the U, B, V measures clearly provide the ingredients of a coarse integral equation from which the original energy distribution $F(\nu)$, very much blurred by the breadth of the U,B,V bandpasses, can be recovered. This is so because the (B-V) and (U-B) colors are related to the first derivatives of the energy distribution function. This was realized by McCrea (144) and by Kardashev & Komberg (123), and they set out to derive $F(\nu)$ from the U, B, V measures. Sandage (180) made a more detailed study using more extensive data.

<u>Correlations between colors and redshifts</u>. - McCrea (144) pointed out that the colors of QSO's are correlated with their redshifts, and Kardashev & Komberg (123) and Barnes (19) independently discussed these correlations. McCrea realized that a relationship between colors and redshift must be due to the intrinsic form of the energy distribution emitted by the objects. When $F(\nu)$ is recovered from the U, B, V measures, the QSO's divide into two distinct groups, one in which $F(\nu)$ is concave to the ν axis or not notice-

ably curved, and one in which $F(\nu)$ is convex to the ν axis. Of the QSO's with redshifts available at the time of McCrea's work, all those in the "concave" group were found to have $z \leq 0.7$, with an average $z = 0.5$, and all in the "convex" group had $z > 0.8$, with an average $z = 1.0$. The correlation becomes even more striking if one plots $Q = (U-B) - (B-V)$ against z; the scatter is less than in the plots of (U-B) and (B-V) alone.

Kardashev & Komberg (123) arrived independently at the conclusion that the colors give information on the energy distribution being received through the U, B, V filters. Sandage (180), with more extensive photometric data, assumed that there is an intrinsic $F(\nu)$ distribution, similar for all QSO's whatever their redshift, and derived its form from the measured (U-B) and (B-V). With an $F(\nu)$ that has some structure in it - changes of slope, maxima and minima - then one samples different parts of such a curve in looking at QSO's with different redshifts through the U, B, V filters with fixed bandpasses. The curve for $F(\nu)$ derived by Sandage is called Sandage's composite curve (SCC); it is the average from 43 QSO's. It has a maximum near $\lambda_o = 2800\text{Å}$ and a depression near $\lambda_o = 2100\text{Å}$, features which are not present in the observed spectrum scans by Oke (157).

The form of the SCC flux distribution was suggested by Strittmatter & Burbidge (217) and by Lynds (134) to be due to the inclusion of the emission lines in the band passes of the U, B, V filters, the difference from the spectral scans lying in the fact that in the latter, the emission lines are excluded as far as is possible.

One can take a simple form for the basic continuous energy distribution, i.e. either (1) or (2):

$$F(\nu) \propto \nu^{-n} \tag{1}$$

$$F(\nu) \propto e^{-\nu/\nu_o} \tag{2}$$

The first gives a continuum whose slope at a given frequency is independent of redshift z for any n. The second gives a continuum whose slope increases linearly with (1+z). Strittmatter & Burbidge (217) took the form (1), with n = 1, and adopted a set of emission-line equivalent widths based on measures by Oke (157) and eye estimates in a number of QSO's (51). They computed the run of U-B, B-V, and Q with z, and found that the computed curves represented quite well the observed run of these quantities, though the observed points had considerable scatter about the computed curves. The scatter in the plots of (U-B) and (B-V) was much larger than that in the plot of Q, and was deduced to be primarily due to the effect of variations in the slope of the continuum among the QSO's. Since Q is a difference, most of the scatter due to fluctuations in the continuum slope should disappear, and indeed the observed scatter in the plot of Q was found to be less (217). The remaining scatter may be attributed to differences in line strengths among the QSO's.

The K-correction for QSO's. - For any class of distant objects which may be used for tests of various cosmological theories, such as the normal or radio galaxies, or QSO's, the measured apparent magnitudes have to be corrected for the so-called "K-effect" (Humason, Mayall, & Sandage (116)), which arises because the standard filters admit different regions of the intrinsic energy curves of objects with different redshifts. Sandage (180) used his derived curve SCC to compute K-corrections as a function of z, and tabulated them normalized to z = 1.0 which falls in the middle range of the observational data. He pointed out that the magnitude corrections are very small except near z = 0, because, except for the effect of the emission lines, the SCC curve is fairly close to $F(\lambda) \propto \lambda^{-1.0}$, though it departs most at the longer wavelengths. If the form were exactly that given above, the correction would be zero at all redshifts.

Polarization of continuum radiation. - Kinman et al. (127) measured a degree of polarization amounting to about 20% in 3C 446, after its rapid increase in brightness which will be described in the next section.

Mechanisms for Producing Continuum Radiation

Several possible physical mechanisms which may give rise to the continuous radiation in different parts of the spectrum have been suggested: thermal emission from a hot gas, coherent plasma oscillations, synchrotron radiation, Cerenkov radiation, and the inverse Compton process. As just described, in 3C 273, and probably in other QSO's also, most of the radiation appears to be emitted by a non-thermal process, though the possibility cannot be excluded that some part of the optical continuum is thermal bremsstrahlung.

The radio properties of the QSO's are very similar to those of the radio galaxies, and it is well established that most of this radiation is due to the synchrotron process. Many authors have considered that the synchrotron mechanism is responsible for the bulk of the radiation all the way from radio to optical frequencies (see e.g. (142)). Strong evidence that the optical flux is of synchrotron origin is provided by recent observations of 3C 446 by Kinman et al. (127) which show that a high degree of linear polarization is present. As will be seen when the theories are discussed, for some classes of models difficulties arise if it is supposed that the radio and millimeter flux (in 3C 273) is emitted by the synchrotron process. Therefore Ginzburg & Ozernoy (93) have suggested that coherent oscillations may be responsible for this radiation. Stein (213) discussed Cerenkov radiation as well as the other possibilities, in considering the millimeter-wavelength radiation in 3C 273.

Given a large flux of low energy photons, then, in inverse Compton collisions with high-energy electrons or positrons a fraction of these photons can be lifted in energy. Thus some part of the flux observed may originally have been emitted at much lower frequencies and may have been lifted by this process. More discussion of all these mechanisms will be given later in the section on theories.

VARIATIONS IN THE FLUX EMITTED BY QUASI-STELLAR OBJECTS

Optical Variations

Following the identification of the first QSO, 3C 48, Smith & Hoffleit (210) looked back on old plates of the Harvard plate collection to attempt to determine whether it was variable in light. They concluded that there was no detectable variation within the rather large errors ($\sim 0\overset{m}{.}3$) which are present in the old plate material. However, the first observations using accurate photoelectric methods by Matthews & Sandage (142) showed that 3C 48 is varying in optical flux, by about $0\overset{m}{.}4$ over about 13 months. In addition to this they reported that a variation of the order of $0\overset{m}{.}04$ in a period of 15 minutes in October 1961 had been measured, and they concluded that night to night variations, as well as the variations over periods of months, were real.

Following the discovery of 3C 273, Smith & Hoffleit (211) and Sharov & Efremov (204) attempted to measure the light curve of this object using the old plate collections going back about 70 years at the Harvard and Pulkova Observatories. They found that variations by a factor of ~ 2 over periods of years are seen while shorter period "flashes" with time scales of months or weeks may be present. Smith & Hoffleit suggested that a characteristic period of about 13 years could be detected in the observations, but this result is still in doubt. While many spectra of this object have been taken since 1963, over the past three years there has been no evidence for any spectroscopic variations.

With the identification of considerable numbers of QSO's there is the opportunity to look closely into the question of variability. Sandage has shown (178, 186, 182) that variations are present as follows:

3C 2: $B \geq 21^m.1$ September 1954, $\sim 20^m.5$ September 1960, $\sim 19^m.5$ August 1963, and $\sim 19^m.5$ November 1964.

3C 43: $B \sim 19^m.0$ in 1954 and $B = 20^m.5$ in 1965 (based on two plates taken 11 years apart).

3C 47: $\Delta B = 0^m.20$ based on observations on 2 nights in 9 months.

3C 48: $\Delta B = 0^m.30$ based on observations on 16 nights over 4 years (178). More recently (182) the object has remained fairly constant.

3C 196: $\Delta B = 0^m.27$ based on observations on 9 nights over 45 months. The object has gradually brightened and there was a sudden increase in December 1963.

3C 216: $\Delta B = 0^m.37$ observed on 3 nights in 14 months.

3C 273: The most recent observations in the last two years show that the object has not varied by more than $\Delta B \sim 0^m.4$ though larger variations were detected in the past.

3C 454.3: $B = 15^m.7$ in August 1954, $16^m.75$ in September 1965, and $16^m.55$ in October 1965.

In the case of 3C 2 significant color changes probably occurred. 3C 279 has also varied between the time the Palomar Sky Survey plates were taken, when it was about $16^m.8$, and the time when the first spectra were taken in 1965, when it was about $17^m.8$ (46).

Thus, although the QSO's have only been observed intermittently, variations have frequently been found and it seems probable that optical variability is a common property.

More detailed investigations have been made of 3C 345 and 3C 446. Goldsmith & Kinman (94) observed 3C 345 fairly continuously over a period $\sim$ 100 days in the interval June-September 1965. They found that the object increased in brightness by about $0^{m}.4$ in a period of $\sim$ 20 days and then decreased more slowly, but showed smaller variations in time scales less than a week until early October 1965. A single observation of this object was made later in October by Sandage (180) who found that it had brightened again by about one magnitude. Thus in this object it has been established that large variations occur on a time scale of weeks or less. During the period June-September 1965 it was observed spectroscopically (42) and the structure of Mg II λ2798 was seen to change though there was no detectable change in the total strength of this line relative to the continuum level.

3C 446 had an apparent magnitude of about $18^{m}.4$ in 1964 and 1965, when spectra of it were being obtained (40, 195). However, it brightened by $3^{m}.2$ sometime between October 1965 and June 24, 1966, when Sandage (181) observed it to be about $15^{m}.2$. In the period July-September 1966 it has been studied in detail by Sandage, Westphal, & Strittmatter (187) and by Kinman, Lamla, & Wirtanen (127). In about 10 days in late July it dropped in brightness by about two magnitudes but by early August it was rising steeply again. From the middle of August until late September it has been bright, near 16^{m}, but has varied on several occasions by $0^{m}.5$ to $0^{m}.8$ in time scales of the order of a day. These are the largest short period variations yet observed in a quasi-stellar object. During July 1966 when the object was very bright Sandage obtained spectra and it was found that the lines appeared to be extremely weak, as compared with the strengths in the spectra taken when the object was much fainter. Sandage et al. (187) showed that this could be explained by supposing that the intrinsic line strengths have remained constant and that this apparent weakness is due entirely to the increased continuum emission corresponding to the increase of brightness of about 3 magnitudes.

Radio Variations

Early in 1965 Sholomitsky (118) announced that CTA 102 was showing rapid cyclic variations at radio frequencies near 1000 Mc/s with a period $\sim$ 100 days. Since this result was announced several groups have attempted to check on the reality of this observation, e.g., Maltby & Moffett (140), who checked their records of observation of this object during or adjacent to the period observed by Sholomitsky and close to his observing frequency. No confirmation of the variations has been obtained, and thus it is not generally accepted at the time of writing. However, also in 1965, Dent (73) announced that he had found a secular variation in 3C 273B at a frequency of 8000 Mc/s such that it was increasing about 17% per year. He also had weaker evidence for variation in 3C 279 and 3C 345. Maltby & Moffet (141) then investigated this object at a number of frequencies and showed that there appeared to be a secular increase in flux down to frequencies of about 970 Mc/s, below which there is no significant variation observed.

Kellerman & Pauliny-Toth (124) have looked at variations of a number of QSO's at frequencies of 750 Mc/s and 1360 Mc/s, using observations made in 1962 and 1963, and in 1965 and 1966. They have combined them with other observations made at higher frequencies 2700 Mc/s, 5000 Mc/s and 15000 Mc/s at NRAO and at other observatories to find variations as follows. 3C 279 in which Dent (74) first reported variation shows very large variations and its flux has been increasing steeply. The variations in 3C 273, found by

Dent, have also been confirmed, and 3C 345, 3C 418 and 3C 454.3 have been found to be variable. In addition to this the object 3C 84, which is a source in the nucleus of the Seyfert galaxy NGC 1275, is also shown to vary. This latter variation was first shown to exist by Dent (74) at 8000 Mc/s. Other radio sources which are variable are NRAO 190 for which there is no optical identification, and 3C 120 which is a radio galaxy.

In 3C 273 Epstein and his collaborators (81, 82) have shown that significant changes in the flux at 3.4 mm are taking place on a time-scale of months or less. In general, however, as far as the observations have been carried out, radio variations have not been found to take place on such short time scales as has been found for the optical variations.

Interpretation of Variations

The condition that a large change in flux takes place in a time τ sets a limit to the size of the region R such that $R \leq c\tau$. This condition can only be relaxed if the matter which is giving rise to the radiation is itself moving at relativistic speed.

This question has been considered by Terrell (221, 222), Williams (227), and Noerdlinger (152) for cases in which the emitting surface is moving non-relativistically. The results by Terrell will be summarized briefly. He considered a fluctuating source consisting of a spherical surface of radius R oscillating in brightness with a period $\tau_o = 2\pi/\omega_o$ measured in its own reference frame, with all parts fluctuating in phase. He showed that

$$R \leq \frac{2c\tau_o}{\pi}\left(\frac{\bar{L}}{\Delta L}\right), \qquad (3)$$

where $\bar{L}$ is the mean luminosity and ΔL the fluctuation. If we wish to consider fluctuations as rates of change of luminosity then since for sinusoidal fluctuations $|dL/dt| < \pi\Delta\bar{L}/\tau_o$,

$$R \leq 2c\overline{L}\left(\left|\frac{dL}{dt}\right|\right)^{-1} \tag{4}$$

and this expression applies to fluctuations which are not sinusoidal. For an observer not in the reference frame of the source the observed period is $\tau = \tau_o(1+z)$ so that (4) becomes

$$R \lesssim \frac{2c\overline{L}}{(1+z)}\left(\left|\frac{dL}{dt}\right|\right)^{-1}. \tag{5}$$

For variations in flux to be well established observationally, it is usually the case that $\Delta L \sim \overline{L}$. Under these conditions we see that it is appropriate to use the simple condition $R < c\tau$. Thus the importance of the flux variations is that they set limits to the sizes of the objects which are now in the case of 3C 446 ~ one light day. The fact that the line-producing region did not change during the period of variations of 3C 446 shows that this region is much larger than the source giving rise to the continuum. In the case of 3C 345, however, no significant apparent changes in line strength occurred during a period when the continuum was changing in strength. Thus in this case it may be that the line-producing region and the continuum-producing region are comparable in size, though the uncertainties are greater because the total change in light was much smaller in 3C 345 than it was in 3C 446.

In the section discussing theories, it will be seen that there are severe problems posed by the limit $R < c\tau$, if the QSO's are at cosmological distances. For this reason, Rees (168) has proposed that the emitting surface is moving relativistically. In this case the surface will appear to be moving faster than the speed of light and the limitation can be relaxed to the form $R < 2c\tau\gamma$, where $\gamma = [1 - (v^2/c^2)]^{-\frac{1}{2}}$.

Model to explain variability of Mg II λ2798. - Burbidge & Burbidge (42) and Dibai & Pronik (77) observed variation in the structure and intensity of the line Mg II $\lambda 2798$ in 3C 345. Shklovsky (207) has proposed a model to account for this. He suggests a dimension of $R \sim 10^{16}$ cm for a region in which Mg is mostly in the singly ionized state. As long as this is the case, such a region will be optically thick to Mg II $\lambda 2798$ radiation. If a powerful flux of relativistic particles impinges on such a condensation, then, since the cross-section for excitation of the upper level of Mg II $\lambda 2798$ is some orders of magnitude greater than the cross-section for second ionization, a large flux of Mg II $\lambda 2798$ quanta will first be generated inside the condensation. This flux cannot immediately escape, as long as most of the Mg exists as Mg^+, but an increasing degree of double ionization will follow. The plasma inside the condensation will be intensely heated in less than 10^5 seconds, and, once the Mg is in the form Mg^{++}, it will become transparent for the resonance quanta of Mg II $\lambda 2798$. A burst of line radiation can thus be emitted by such small regions, followed by fading, the time scale of the consequent variation being $\sim 10^5$ sec.

RADIO PROPERTIES OF QSO'S

The majority of the quasi-stellar objects were first identified through their radio emitting properties, and at the frequencies at which the radio surveys have been conducted they appear over a wide range of flux levels, as do the radio galaxies. If they are at the distances indicated by their redshifts, then, because the redshifts are large compared with those of the radio galaxies, many of them are emitting at the power levels of the strongest radio emitters, in the range 10^{43} - 10^{45} erg/sec.

The distribution of radio brightness for most of the objects has not been determined. A number of QSO's show similar structures to those found for radio galaxies (150), i.e., they are double with large separations between the two components. Examples are 3C 47 (196), MSH 14-1<u>21</u> (102, 225, 39) and 3C 9 (194). The separations between the two components in these three cases, assuming the objects are at cosmological distances with $q_o = 1$, are: 3C 47, 207 kpc; MSH 14-1<u>21</u>, 133 kpc; 3C 9, 130 kpc. If the objects are local, (d = 10 Mpc) the corresponding separations are: 3C 47, 3.4 kpc; MSH 14-1<u>21</u>, 1.8 kpc; 3C 9, 1.9 kpc.

In many cases also, the QSO's have at least one radio component with a diameter corresponding, at a cosmological distance, to a size comparable to those found for radio galaxies in general (150), i.e., ~ 50 kpc. Such sizes, together with the high power levels, mean that the energy content of the sources in relativistic particles and magnetic flux has minimum values $\sim 10^{60}$ ergs (49). Many of the QSO's, however, unlike most radio galaxies, have at least one exceedingly small radio component which may, or may not, be the only component (the radio galaxy NGC 1275 has a small central component).

The suggestion that some of the radio sources would have very small angular diameters came first from attempts to interpret the radio spectra. It is well known that the radio sources have spectra of the form $P(\nu) \propto \nu^{\alpha}$, where α is an index with a median value near -0.7 (71). In a fraction of the sources examined the spectra show a pronounced curvature, getting flatter as one goes to longer wavelengths. These sources have large brightness temperatures, suggesting small sizes. Frequently in these cases a maximum is reached in the spectrum and the flux appears to decrease at longer wavelengths. To explain this property LeRoux (129), Slish (209) and Williams (228) proposed that the curvature of the low frequency part of the spectrum is probably due to synchrotron self-absorption.

From formulae given by Dent & Haddock (75) and Williams (228), if the radio spectrum is known, so that the frequency at which synchrotron self absorption sets in can be estimated, the angular size can be calculated as a function of the magnetic field strength. For example, in the cases of the quasi-stellar sources 3C 48, 119, 147, 298, CTA 21, and CTA 102, with assumed values of $B = 10^{-4}$ gauss, Williams obtained maximum angular diameters of 0.4", 0.3", 0.2", 0.6", 0.01", respectively.

Methods which are being used to investigate the structure of the sources of small angular size are:

(1) Long base line interferometry at Jodrell Bank and at Malvern (6, 8, 18,2). These groups are now working with effective baselines of up to 604,000 wavelengths at a frequency of 1422 Mc/s. The NRAO astronomers at Greenbank, West Virginia, have also carried out similar work (62).

(2) The method of lunar occultations (103,106).

(3) The method of using the irregularities in the interplanetary plasma which cause scintillations of small diameter sources (104, 65).

Detailed studies have been carried out, particularly for 3C 273 (103,106), and a considerable number of sources have been studied using long base line interferometry. We discuss first the results achieved by this method.

The following QSO's have been shown to have sizes < 0.1" by the observations at 1422 Mc/s of Barber et al. (18): 3C 279, 3C 345 and 3C 380. These objects all show evidence for large fluxes at high frequencies (75). A number of other QSO's have been studied by the interferometer technique at 408 Mc/s and 3C 286, 147, 48, 273, 287, CTA 21, CTA 102, 3C 119, 3C 138, 3C 279, 3C 345, and 3C 380 all have significant fluxes coming from sizes ≤ 0.″5.

The method of lunar occultations is being used to determine positions of sources and structural characteristics by a number of groups, notably by

Hazard, and also by von Hoerner; they have worked extensively on 3C 273. Hazard, Mackey & Shimmins (103) first showed that this object was double with a separation of $19''.6$ and that the two components had very different spectra. Component A had a value of α of about -0.9, while 3C 273B which is associated with the optical object and agrees in position with it to about $0''.1$ had a spectral index with $\alpha \sim 0$. Both components are elongated along the line joining them. It appears now from the work of von Hoerner that the structure of both components depends strongly on frequency. B is a single strong component about $2''$ wide at 2695 Mc/s; at 735 Mc/s it shows a halo about $6''$ long and a core $\leq 1''$ which emits 30% of the flux. The core is less pronounced at 405 Mc/s, but at the lower frequencies B shows a deep minimum at the center. A seems to have a central dip at 2695 Mc; at 735 Mc it has a halo about $10''$ long and a core $< 1''$ (with 30% of flux) at the lower frequencies. A has a length of half power points of about $4''$, but shows a faint, very flat extension about $23''$ long. According to this more recent work the spectrum of A is a straight line with $\alpha = -0.68 \pm 0.08$. The spectrum of B is a straight line only above 400 Mc/s, with $\alpha = +0.25 \pm 0.08$; it cuts off toward lower frequencies. Each component is then divided into an outer part and a central part $4''.8$ long. The central spectrum of A is still straight with $\alpha = -0.82 \pm 0.22$ while the low-frequency cutoff for the center of B is very steep. Both outer halos are very similar and give $\alpha = -0.45 \pm 0.20$. Such a complex structure has so far been found only in 3C 273, but it may be expected to be generally present.

Method (3) has been used to show that the angular sizes of the QSO's 3C 48, 119, 138, and 147 have components that lie in the size range $0''.3$ to $0''.8$ (104). Scintillation measurements have now been carried out at Arecibo (66, 67) for a considerable number of sources. Also, according to Bolton (25) a considerable amount of scintillation data have been obtained by Ekers with the 210-ft. Parkes radio telescope.

PROPER MOTIONS

If the QSO's were really local objects, within (say) a few hundred parsecs of the Sun, as had to be considered in the original discussion by Greenstein & Schmidt (97) on whether they could be collapsed stellar objects with large gravitation redshifts, then proper motions might have been expected to be detectable.

Jeffreys (119) made a study of the proper motion of 3C 273, using 14 plates covering the period 1887-1963. The plate material was not homogeneous, but an attempt was made to reduce the systematic errors in such a determination by using a large number of reference stars. The absolute proper motion was found to be:

$$\mu_\alpha = +0\overset{''}{.}0009 \pm 0\overset{''}{.}0025/\text{yr}$$
$$\mu_\delta = -0\overset{''}{.}0012 \pm 0\overset{''}{.}0025/\text{yr}.$$

Because of the position of 3C 273, in a direction approximately at right angles to the direction of the Sun's peculiar motion, Jeffreys concluded that the object was likely to be more distant than 2000 pc (unless it were travelling parallel to the Sun at the same speed). Its high galactic latitude would then mean that, if it belonged to our Galaxy, it might well have a different galactocentric velocity from that of the Sun, which should in turn lead to a detectable proper motion unless it were at an even greater distance, effectively outside the Galaxy.

Luyten & Smith (133) made a study of 12 QSO's, and essentially the same result was found for all 12 objects: the relative proper motions were of the same order of magnitude as the estimated mean errors. The proper motion measured for 3C 273 did not agree with that measured by Jeffreys. The 12 objects were averaged in 3 groups, and the mean proper motions were found to be the inverses of the expected parallactic motions of the comparison stars, as would be expected if the QSO's have zero absolute proper motion. Luyten & Smith concluded that the QSO's, as effectively stationary objects with stellar images, are ideal objects for determining the corrections from relative to absolute proper motions.

SPATIAL DISTRIBUTION

With only ~ 120 QSO's positively identified it is too early to gain much information by looking at the distribution of these objects in the sky. The work of the Cambridge radio astronomers has shown that there is a fairly high degree of isotropy present as far as the radio sources as a whole are concerned. However, in the large scale surveys complete identifications into the two non-galactic categories of quasi-stellar objects and radio galaxies have not been made, and it is premature to claim (131) that the results obtained so far suggest that the QSO's are at cosmological distances. It is of some interest to see whether the QSO's are distributed in such a way as to suggest that they may have some physical relationship with other extra-galactic systems. The evidence bearing on this comes from different directions and is very preliminary.

The relation between quasi-stellar objects and clusters of galaxies. - If the objects are at cosmological distances they are approximately 3^m brighter than the brightest galaxies in clusters. In addition, there will be an appreciable K correction for the galaxies which will not apply for the QSO's and this, for a redshift of z = 0.5, amounts to nearly 2^m (184). Consequently the QSO's will appear approximately five magnitudes brighter than the brightest galaxies in clusters in which they might lie for redshifts near 0.5. The majority of identifications of QSO's have been made with the 48-inch

Palomar Sky Survey plates and the normal limit of these plates is $20^m.0$ (visual). A preliminary conclusion is therefore that clusters would only be identified on these plates if the QSO's were brighter than 15^m. Only 3C 273 is brighter than this and certainly no cluster is associated with it. However, it is known that there is only a weak correlation of redshift with apparent magnitude, and there are eleven QSO's now known besides 3C 273 with redshifts $z < 0.5$, and of these four have magnitudes brighter than 16^m and seven have magnitudes brighter than 17^m. Also, 3C 232 has a redshift $z > 0.5$, but is brighter than 16^m. In these cases the K correction for the galaxies, if they were present, would be less than $1^m.9$, and we might expect therefore that the difference between the apparent brightness of the QSO and cluster galaxies would often be less than 4 magnitudes, so that galaxies would be detectable. However, none have been seen.

In a number of cases plates reaching 1-2 magnitudes fainter than Sky Survey plates have been taken for fields incorporating the QSO's, and inspection of those plates shows no galaxies. In the case of 3C 48 Sandage & Miller (184) have used a special emulsion with which they were able to reach apparent magnitude $24^m.5$ (blue), and no galaxies were found.

<u>Are quasi-stellar objects associated with individual bright galaxies?</u> - If it could be established that QSO's are associated with a particular kind of galaxy, then it would be strongly presumed that they have some genetic relationship with these galaxies. Evidence bearing on this possibility has recently been presented by Arp (10, 11). He concluded that galaxies in his Atlas of Peculiar Galaxies (12) lie closer to the radio sources than would be expected if the radio sources were distributed at random with respect to the peculiar galaxies. He noticed that radio sources with similar flux densities tend to form pairs separated by from 2° to 6° on the sky and

that there was a tendency for a certain class of peculiar galaxy to fall approximately on the line joining the pair. These peculiar galaxies are often elliptical galaxies which he believes show evidence for structures which may have been ejected from them. In some cases there is evidence that more than two radio sources are associated with a given peculiar galaxy.

The double nature of radio sources is well established. In fact Arp's hypothesis is in a sense only an extension of the previously well-known observation that the bulk of the radio sources are double, but Arp has attempted to establish the existence of double sources with much wider angular separations than accepted before. However, in Arp's case some of the objects have previously been identified with QSO's and apparently more distant radio galaxies.

Unless all of the evidence presented by Arp is due to chance coincidence, then it must be concluded that the QSO's do not lie at cosmological distances. At present most workers are somewhat skeptical of the data, and intensive work on this aspect of the QSO's is underway.

<u>Similarities in pairs of radio sources</u>. - There is some evidence concerning the similarity of pairs of radio sources. Moffet (149) has shown that the radio sources 3C 343 and 3C 343.1 have very similar power levels and very similar radio spectra, though they are separated by $29'$. They are both exceedingly small radio sources with angular sizes $\leq 10''$ so that the ratio of separation to size exceeds 200. No optical identifications have been made for these sources, but the curved radio spectra strongly suggest that they are quasi-stellar objects. Moffet has estimated that there is a probability $\sim 10^{-6}$ that the objects are not physically connected. If they are at cosmological distances their separation in space would be so large that physical association is quite unreasonable. If they are physically connected, one might argue therefore the objects have a much smaller separation

(at a distance of 10 Mpc this would be ~ 90 Kpc) and both sources might have been ejected from a local QSO, or might be a pair of identical QSO's which have been ejected from a galaxy. However, the case of the pair of radio sources forming 3C 33 (Moffet (148)) should also be mentioned. Here a similar situation prevails. The two sources are small and very similar and the ratio of separation to size is ~ 16. In this case an optical galaxy is identified as the object giving rise to the pair of radio sources, and if this identification is correct the pair lies at a modest distance.

There is only one QSO known so far lying very close in the plane of the sky to a bright galaxy with some optical peculiarities. This is 3C 275.1; it lies very close to NGC 4651, so close that the optical identification was originally thought to be with NGC 4651. The galaxy has a faint tail or jet extending approximately in the direction of the QSO.

CORRELATIONS AND STATISTICS

Redshift - Apparent Magnitude Relation

If the quasi-stellar objects are at cosmological distances, the m-log z relation may be used to investigate cosmological models. Sandage (179) made a plot of the relation between apparent magnitude and redshift for the ten QSO's whose redshifts were known at that time, alongside a similar plot for the radio galaxies, and the QSO's already showed considerable scatter. No correction for K-effect was applied to the magnitudes of the QSO's; as already discussed, this correction is very small for QSO's unless their continua have slopes differing considerably from that given by $F(\nu) \propto \nu^{-1}$ (180).

An alternative way of correlating optical luminosity with redshift is that adopted by Schmidt (194). For a chosen cosmological model (evolutionary, with $q_o = +1$) he calculated the monochromatic flux from nine QSO's at an emitted frequency of 10^{15} c/s, i.e. at a rest wavelength of 3000Å, and examined whether these fluxes were approximately the same for all the objects. Since spectral scans covering the whole wavelength range, from near 3000Å to 9000Å, did not exist, he used the UBV photometry and found that the fluxes of the nine objects were consistent with an evolutionary cosmology with $q_o = +1$, with a scatter whose extreme range is a factor 20.

As new redshifts have become available, the scatter in the apparent magnitude-redshift relation has become larger instead of smaller (108). A plot of the present data will be found in (50). What little correlation there is shows a scatter of a similar order of magnitude to the total span of the relation. Indeed, with the luminosity variations shown by individual QSO's (more than 3 magnitudes or a factor of nearly 20 in the case of 3C 446), such scatter is not surprising. The plot represents, in fact, the quality of the intrinsic luminosity function of the QSO's, rather than a meaningful distance-redshift relation.

Redshift - Radio - Flux Correlation

Hoyle and Burbidge (108) plotted the logarithm of the radio flux (or radio apparent magnitude) at 178 Mc/s against (1+log z) for the QSO's in the 3C R catalogue and this showed even more scatter than the similar plot of redshifts against optical apparent magnitudes. There was no sign of any correlation, and this implies that the range in apparent radio fluxes is not determined by a range in distances but entirely by the intrinsic spread in the radio properties of the QSO's.

Bolton (25) suggested that such a plot made with radio measures at the comparatively low frequency of 178 Mc/s, contains objects with a variety of radio spectra, and he plotted (1+log z) against radio magnitude at 1410 Mc, for QSO's in the Parkes catalogue. While such a plot shows an equally large overall scatter, one can make a distinct separation into two groups if one considers objects with flat or relatively flat radio spectra as one group and objects with steep radio spectra as another group. The objects with steep radio spectra show no positive correlation, and Bolton suggested that this is simply a reflection of a very large dispersion in the relevant intrinsic radio luminosities. The QSO's with flat radio spectra may all undergo synchrotron self-absorption and the radio emission may be emanating from a very small volume; Bolton suggested that such objects might have less intrinsic spread in their high-frequency radio radiation, and, while there is no very distinct relationship, the scatter for the flat-spectrum sources is considerably lower than for the others.

Log N - Log S Curve

For a uniform distribution of sources of radiation in Euclidean space, with a luminosity distribution that is independent of distance, a plot of log N against log S (N = number of sources brighter than flux S) should have a slope of -3/2. For large redshifts this will be modified by (1) the K-correction (but this is small), (2) the fact that the redshift reduces the brightness over and above the inverse square law, and (3) an increased density of sources in the past in an evolutionary universe.

In the steady state universe this last effect is not present, but in the evolutionary models the second effect overwhelms the third. Thus cosmological effects will tend to reduce the slope of the log N - log S plot.

In the early work on the source counts of all radio sources by Ryle & Scheuer (176) the slope of the log N - log S curve was about -3, much steeper than any predicted values. Next a survey by Mills, Slee, & Hill (145) gave a slope of about -1.8. The next survey was made in 1959 (78) and gave a slope of about -2. A further survey was then carried out with greatly increased precision by the Cambridge group (202) and this gave a slope of -1.8. Most recently a survey has been carried out by Bolton, Gardner, & Mackey (32) and this gives a slope of -1.85. Thus there is now good evidence from several independent groups that the slope of the log N - log S curve for all sources is near -1.8.

Since the cosmological effects all tend to flatten the curve to values below -1.5, it is obvious that other effects must be present to explain the observed slope. Either an excess of faint sources, or a deficit of bright sources is required. If an excess of faint sources is present, this could be caused by the intrinsic brightness of a source being a function of its time of formation in an evolving universe, and the effect has been used as a strong argument against the steady-state cosmological theory. If the slope were due to a deficit of bright sources, this could be explained by postulating a local irregularity in distribution.

These investigations were carried out at a time when the majority of the radio sources remained unidentified, though they were largely thought to be associated with galaxies. Since a considerable fraction of the 3C R sources are now identified, Véron has plotted the log N - log S curve separately for radio galaxies and QSO's (224), and has found that for the radio galaxies the slope is -1.5, while for QSO's it is about -2.2. The slope for all 296 sources in the revised 3C R taken together was made earlier by Ryle & Neville (174) and gives a slope of -1.85. The value of -1.5 obtained for the galaxies is presumably due to the fact that the size of the region over which the 3C survey sources have been found is small enough so that the Euclidean space approximation holds. The greatest redshift known so far for a radio galaxy is that for 3C 295, $z = 0.46$, and the majority of the radio galaxies so far studied spectroscopically have $z \leq 0.2$. Thus in this survey at least the departure from the $-3/2$ law arises from the QSO's. There are two possible explanations for this. If the QSO's are cosmological, then we must attribute this steeper slope to evolutionary effects in an evolving universe, as has been done by Longair (131). Alternatively, if they are local, this slope must be attributed to the local conditions under which these objects were ejected from galaxies.

A discussion of effects to be expected in the log N - log S plot for much fainter sources on the cosmological and the local hypotheses for QSO's was given in (1).

Another type of argument to explain the observations and preserve the steady state theory has been proposed (197, 198,201). This involves the idea that another class of intrinsically very faint objects - QSO's with zero redshift, lying at characteristic distances of $\sim$ 100 pc - is present. There is no direct evidence, however, for the existence of such objects.

The assumption underlying the studies of the log N - log S curve for cosmological purposes is that the slope is to be accounted for by a distance-volume effect. Hoyle & Burbidge (108) tested this for a sample of about 30 QSO's from the 3C catalogue for which redshifts were known, and showed that the log N - log S plot for these objects has a slope near to -1.5, not quite as steep as the value of -1.8 obtained from the counting of all radio sources and not as steep as the value of about -2.2 obtained by Véron for all QSO's in the 3C catalogue. The particular value of the slope, depending at the bright end on very few points, is not significant. What does appear to be significant, however, is that even this small sample of QSO's gives a log N - log S slope near -1.5. The distance volume interpretation requires that the objects with smaller S are at greater distances, and if redshifts are cosmological in origin small S must be correlated with large z. From the redshift apparent radio magnitude plot for these objects it is obvious that no such correlation exists. Thus if it is assumed that the distance-volume interpretation of the log N - log S relation holds, it must be concluded that the redshifts have nothing to do with distances.

This investigation was criticized by Longair (131), Sciama & Rees (199), and Roeder & Mitchell (172), who thought Hoyle & Burbidge had concluded unconditionally that redshift had nothing to do with distance. However, the conclusion stated above can be inverted to the form: If the redshifts are related to distance in the usual cosmological sense, then the distance-volume interpretation of $NS^{3/2} \approx$ constant must be abandoned for the sources in this particular sample. Consider the sources in a shell between distances r and r + dr. Provided these sources have an intrinsic scatter in their radio emission they will exhibit a log N - log S curve. If all such shells have the same log N - log S curve then summation of all shells will give a curve related to intrinsic scatter, not to distance. This is the point made by Bolton (25). In order that all shells give the same log N - log S curve, however, it is necessary for the average emission to vary in a special way from one shell to another. This indeed is the suggestion of Longair and of Roeder & Mitchell. It requires the average emission to be a function of r and hence of the epoch. Such an interpretation is evidently in disagreement with the strict steady-state theory (199).

Finally, the status of the radio sources which remain unidentified should be mentioned, since they affect the statistics. In the 3C, many sources with good radio positions, in unobscured fields, lie in apparently empty fields, to the limits of the Palomar Sky Survey. Véron (224) believed that these are probably QSO's, while Bolton (25) believed that they are probably radio galaxies. At present, it is the reviewer's opinion that Bolton's view is the more likely to be correct. Sandage is carrying out a search of the empty fields with the 200-inch Palomar telescope, which goes to a limit some 3 magnitudes fainter than the Sky Survey.

THE NATURE OF THE QUASI-STELLAR OBJECTS

When large redshifts were first found in QSO spectra, and shown (97) to be probably Doppler shifts, it was assumed by nearly everyone that they were due to the expansion of the universe and the QSO's were consequently at very large distances. Terrell (221), however, suggested that QSO's are entities that have been ejected from the nucleus of our Galaxy in an explosive event like those giving rise to radio galaxies. Hoyle & Burbidge (107) extended this to the possibility that they might have been ejected from the strong nearby radio galaxy NGC 5128. Arp (10, 11) further extended it to suggest that pairs or groups of radio sources, including QSO's, are ejected from a class of peculiar galaxies. There are difficulties in interpreting the observations in terms of all of these possibilities, and these problems will be briefly discussed.

Cosmological Hypothesis

The difficulties here stem mainly from the observed optical and radio variations and the consequent small dimensions set by the short time scales and the condition $R \leq c\tau$, coupled with the fact that, at cosmological distances, the objects are emitting very large amounts of radiation (40 times the optical radiation of the brightest galaxies, on average, and, including the microwave and infrared radiation in 3C 273, some 10^{47} erg/sec.

The first indications that there were difficulties with simple homogeneous models came from the discovery of the time variations of 3C 273B at 8000 Mc/s by Dent (73) and interpretation of the data. The frequency at which synchrotron self-absorption sets in is related to the size of the object, the flux radiated at that frequency, and the magnetic field strength. For the parameters thought to be appropriate for 3C 273B at that time the time scale for variation came out to be $\tau \geq 23$ years, for a frequency $\nu = 400$ Mc and magnetic field $B \geq 10^{-5}$ gauss. In his original calculation of this result Dent made a numerical error which was corrected by Field (85). If the radio emission at $\nu = 400$ Mc to which the spectrum extends with no cutoff arises from the same region as that giving the secular variations at 8000 Mc, then the value $\tau \geq 23$ years was just compatible with Dent's result that the flux increased by 40% in $2\frac{1}{2}$ years. Otherwise it must be concluded that either the synchrotron mechanism is not operating, or else that the object is not at a cosmological distance. If $\nu = 8000$ Mc is used in the self-absorption equation, the relevant dimension is 0.5 l.y. for 3C 273B at a cosmological distance. Rees & Sciama (169) assumed that the source 3C 273 contains an exceedingly small component with a dimension $\sim 10^{-3}$ seconds of arc buried in a much larger source with a dimension $\sim 0.''5$. Then for a large enough magnetic field in the central source, $B \geq 1$ gauss, they were able to account for the variable flux at 8000 Mc/s.

Hoyle & Burbidge considered a more general class of models in which the magnetic field in the object is not assumed constant and the radio spectrum is controlled by variations in the magnetic field. It can then be shown that the flat form of the spectrum observed in 3C 273B can be obtained, and that it continues down to 200 Mc without being self-absorbed. This type of model leads to a situation in which different shells are contributing to the radio flux in different energy ranges. Hoyle & Burbidge concluded that such a model for 3C 273B could satisfy the requirement that the process operating be the synchrotron process and that it could be at its cosmological distance.

Ginzburg & Ozernoy (93) concluded that under certain conditions, provided that there is equipartition between particle and magnetic energies, in an inhomegeneous model more energy is required to give the observed flux. They suggested coherent plasma oscillations. For the QSO's in general it appears that the very small source sizes require that if the synchrotron mechanism is operating the conditions are actually very far from the equipartition condition (229).

Stein (213) considered the varying microwave radiation in 3C 273, and showed that magnetic fields near 10^5 gauss must be invoked for plasma oscillations to be responsible. A consistent model producing this radiation by the synchrotron mechanism, at a cosmological distance, does not seem possible.

A further problem caused by the limit $R < c\tau$ arises through the very large radiation density within the small volume and the consequent competition between the synchrotron mechanism and the inverse Compton process as the dominating source of energy-loss of the high-energy particles. Hoyle et al. (110) showed that, in 3C 273, for the synchrotron mechanism to dominate, $B \geq 15$ gauss, while in 3C 446, with a much shorter variation period and consequently smaller dimension, $B \geq 400$ gauss. The electron lifetimes would then be very short so that a large number of co-phased sources of injection or acceleration of charged particles thoughout the object would be necessary.

Woltjer (231a) considered the effect of a non-isotropic radiation field. The Compton process becomes less important for close alignment of the light beam with the magnetic field. For an assumed set of conditions, Woltjer showed that the synchrotron process can dominate over the inverse Compton effect for values of the magnetic field about one order of magnitude smaller than those given above. The magnetic field has to be radial, and the electrons must have very small pitch angles.

Another kind of model in which the flux is emitted from coherent blobs of matter moving at relativistic speed was suggested by Hoyle & Burbidge (109).

As already mentioned, Rees (168) pointed out that a relativistically expanding cloud can increase its apparent angular size at γ_V times the rate given by the usual non-relativistic formula, where $\gamma_V = (1 - \frac{V^2}{c^2})^{-\frac{1}{2}}$, V being the expansion velocity, which relaxes the condition $R < c\tau$. This model was suggested to explain a steep rise in radio emission; probably a model could be constructed involving the acceleration of emitting material that gave a similar result for optical radiation. However, the fluctuation data involve decreases of light as well as increases, and the situation for a fall in apparent magnitude is not so clear in a simple radially expanding model.

It has been suggested (231a) that since at least one galaxy (NGC 1275) is known to show variations in high-frequency radio flux, similar to the variations seen in a number of QSO's, this is evidence supporting the view that the QSO's are at cosmological distances. However, the difficulties encountered with the cosmological models of the QSO's stem, as just shown, from the very high densities of radiation which, in turn, arise because of the very great distances of the objects. No difficulties are encountered if the objects are closer by, and none are encountered in the case of NGC 1275 simply because it lies at a distance of only about 50 Mpc.

Hypothesis That QSO's Were Ejected From Our Galaxy Or A Nearby Galaxy

Terrell (221,222) originated this idea, suggesting our Galaxy as the seat of origin. Hoyle & Burbidge developed it, suggesting NGC 5128. Unless a nearby galaxy is chosen, and unless the explosion occurred long enough ago for the objects to have passed the observer, some objects would be seen approaching the observer, and consequently they would have blueshifted spectra. No blueshifts have been observed. Also, there would not be an isotropic distribution of objects. Preliminary evidence (218) does suggest that there may be an anisotropic distribution of redshifts on the celestial sphere, but more work is needed in this field.

The main objections to this form of the local hypothesis are twofold: (1) No mechanism leading to the ejection of coherent blobs of matter moving at relativistic speeds has been suggested, and (2) The total energy release needed in an event leading to such ejection would be very large.

Regarding (2), the kinetic energies of the relativistically moving objects depend on the masses. Setti & Woltjer (203) estimated the total masses by supposing that the emission line widths were due to large random motions of gas and that there must be a central mass large enought to stabilize the object gravitationally. From this argument they obtained masses of the order of 10^7 - 10^8 $M_\odot$ for 3C 273 and 3C 48 on the local hypothesis. However, their argument is vitiated if the line broadening is not due to mass motions, and, as discussed in the section on line spectra, electron scattering may well be the dominant line-broadening mechanism.

Another method of estimating the mass of a local QSO is to suppose that it does not conserve its mass and that gas is continuously escaping from it. Bahcall, Peterson, & Schmidt (15) considered the absorption lines in some QSO's, particularly PKS 1116+12, as evidence for such mass loss. Estimating lifetimes of 10^8 years for QSO's as local objects, and supposing the average absorption line phase lasts 1/10 of this, with continuous ejection at 17,000 km/sec in PKS 1116+12, the total mass of gas which has escaped was found to be $\sim 10^9$ $M_\odot$. Counter arguments can clearly be raised in which the various assumptions underlying this calculation are questioned; until a definitive model accounting for the absorption lines is produced, the question is controversial.

Hypothesis That QSO's Were Ejected From Many Galaxies

Arp (10, 11) proposed that QSO's (and other radio sources) are ejected from a class of peculiar galaxies. The main problem here is that no QSO's with blueshifted spectra have been seen. It has been shown that, for local objects moving at relativistic speeds, the observer should see a number of blueshifted objects that is $(1+z)^4$ times the number of redshifted ones, where z is the numerical value of the positive or negative shift. For a detailed discussion of the distribution among randomly moving objects one may turn to (50), which gives a summary of work by a number of authors (216,83,153,235).

Selection effects which might modify this result by discriminating against the detection of QSO's with blueshifts have been considered (55), e.g. the relative weakness of emission lines in the infrared which could be blueshifted into the visible region, and the rising intensity of the continuous spectrum in the infrared, but the factor $(1+z)^4$ is a large one and it seems likely that some blueshifts with $z < 0.5$ should have been seen if they occurred in nature.

Partly to avoid this difficulty, Arp suggested that the redshifts are not of Doppler origin, but no new physical possibility has been proposed.

Concluding Remarks

It is clear that there are difficulties with all three hypotheses, and the problem reduces to that of producing a complete model which will satisfactorily account for all the observations. For the cosmological hypothesis, many limitations on possible models are set by the observed variability; for the local hypothesis, a mechanism for ejecting coherent blobs and providing a large energy source is needed; for the more extended local hypothesis, a new physical cause of redshifts is needed.

QUASI-STELLAR OBJECTS AS PROBES OF THE INTERGALACTIC MEDIUM

Mg II absorption. - Shklovsky (206) pointed out that intergalactic Mg^+ should produce absorption due to the resonance doublet of Mg II at λ2798 to the blue of the position of this emission line in QSO's. Since no absorption is detectable, he concluded that the density of $Mg^+ < 8 \times 10^{-13}$ cm^{-3}, and an upper limit $n = 2 \times 10^{-7}\ cm^{-3}$ is set to the intergalactic hydrogen density.

Lyman-α absorption. - Immediately following the discovery that 3C 9 has Ly-α shifted to a wavelength of 3666Å, Scheuer (190) pointed out that if the spectrum showed a continuum below this either the mean density of neutral atomic hydrogen is exceedingly low, or else the ionization is nearly complete. He also did not exclude the third possibility, that the object is comparatively nearby, in which case no appreciable absorption is to be expected. A more detailed investigation using the observational material of Schmidt's on 3C 9 was made by Gunn & Peterson (99). They estimated a depression of 40% in the continuum, giving a number density of neutral atomic hydrogen of $n = 6 \times 10^{-11}\ cm^{-3}$, or a density $\rho = 1 \times 10^{-34}\ gm/cm^3$. However, since the first spectra of 3C 9 were obtained a considerable number of QSO's with Ly-α in the photographic region have been observed and scanner observations of 3C 9 have been made by Oke & Wampler. The observers are now agreed that there is little evidence for any significant depression to the blue of Ly-α. Thus the upper limit to the density is somewhat lower than the value above. As already described, absorption lines seen in PKS 1116+12 (15) may be intergalactic, produced by gas in a cloud or cluster of galaxies in the path length traversed by the light.

Sciama & Rees (200) attempted to interpret some features in the spectral region of 3C 9 below 3300Å as being due to Ly-α absorption and an absorption line of N V with a redshift $z = 1.62$, caused by a hot intergalactic cloud. These identifications were made, however, from a reproduction of the spectral intensity in this region (86) without taking into account noise in the observations near the atmospheric cut-off.

21-cm absorption. - Kohler & Robinson (128) reported the detection of 21-cm absorption in 3C 273 at a wavelength corresponding to $z = 0.0037$. This is almost exactly the mean red shift of the galaxies in the Virgo cluster and thus they concluded that this absorption is caused by a neutral hydrogen cloud associated with the Virgo cluster, 10 Mpc distant. However, the observation is marginal, and so far it has not been confirmed by other radio astronomy groups.

Molecular H. - Bahcall & Salpeter (16) pointed out that limits on intergalactic H_2 may be set by considering the absorption produced in the Lyman band shortward of 1108A. Again objects with $z \geq 2$ are required. This test has been attempted using 3C 9 by Field et al. (86), who detected no absorption. This led to an intergalactic density of $H_2 < \sim 10^{-32}$ gm/cm^3.

Thomson scattering. - Bahcall & Salpeter (16) discussed scattering by electrons in an ionized intergalactic medium, and derived formulae that depend on the cosmological model. For $z \sim 2$ the effect is not yet important, but for large z it will be of significance.

Thus all the observations made so far show no good firm evidence for any intergalactic absorption or scattering. Most investigators have used this result to set very low limits to the density of neutral gas, and have then concluded that the bulk of the mass energy in the universe (assumed by most to be near 10^{-29} gm cm^{-3}) is present in the form of ionized gas, mainly hydrogen. An alternative interpretation would be that the QSO's are local rather than cosmological. Or thirdly, most of the intergalactic matter might be in the form of stars, uniformly distributed, or condensed into small clusters or low luminosity galaxies, or in the form of solid matter, or even in the form of neutrinos.

THEORIES FOR THE ENERGY REQUIREMENTS OF THE QUASI-STELLAR OBJECTS

From the radio spectra of the QSO's, the synchrotron mechanism is most likely responsible for the emission, as is the case for the radio galaxies. If the QSO's are at cosmological distances then the minimum total energies which are required to give rise to the radio emission are of the same order of magnitude as those for the radio galaxies, i.e. $\sim 10^{61}$ ergs (49). The total energy released may be above this minimum value, in the range 10^{62} - 10^{63} ergs, largely in the form of relativistic particles. In the case of the radio sources of very small size associated with QSO's, the minimum total energy required can be much smaller since, for a given synchrotron flux, this total energy is proportional to $R^{-6/7}$ where R is the dimension of the system, so that it might be as low as 10^{58} ergs. However, there are other arguments in this case to suggest that this minimum total energy condition cannot be fulfilled, and that the total energy, largely in the form of particles, must be $\sim 10^{60}$ - 10^{61} ergs confined in a dimension of a few parsecs or less. All of these arguments are based on the assumption that the magnetic field is fairly homogeneous. If one considers a non-homogeneous model (107) somewhat lower total energies may be feasible.

If the QSO's are comparatively nearby then the minimum total energy in the relativistic particles and magnetic fields in a given object is much reduced - to perhaps 10^{55} - 10^{56} ergs in an individual source. However, a very large amount of kinetic energy must then be contained in the relativistically moving QSO. For a mass $\sim 10^{4}$ $M_{\odot}$ and v = 0.6 c, for example, the total energy $\approx 10^{58}$ ergs, and a number of QSO's must be ejected in a galactic explosion. Thus in any case very large energy releases are required.

As for other wavelength regions, 3C 273 at the cosmological distance emits $\sim 2 \times 10^{47}$ erg/sec, mostly in the range 10^{11} - 10^{13} cps. At a "local" distance of ~ 10 Mpc, a flux less by a factor of 10^{4} - 10^{6} is needed. If the QSO's are emitting optical, infrared, and millimeter radiation by the synchrotron process, then in the most extreme situation in which the magnetic fields are as large as 100 gauss (206), the total energy present in the electrons must be about 2×10^{52} ergs, and this must be renewed every 10^5 seconds. Thus, if the objects last for about 10^6 years, the total energy release is about 10^{61} ergs. If the inverse Compton process is operating (and it is not clear whether such a model can be devised), two components are required: an intense source of low frequency photons and a supply of high energy electrons. Since in such a model the photons must be raised many octaves in frequency, most of the energy must reside in the electrons. If, for example, a "machine" generating photons with frequencies as low as 10^4 cps were operating it would require electrons with energies of 10 Gev to lift the photons by the inverse Compton process to $\nu \sim 10^{12}$ cps. It is really not possible to estimate how the energy is divided, but the total energy release must at least $\sim 10^{47}$ t where t, the lifetime of the source, may be about 10^6 years, so again the total will be about 10^{61} ergs.

The various theories proposed to account for the energy emitted in the radio sources have been summarized earlier (52, 49). Since then, a number of new investigations and suggestions have been put forward, which will be summarized here. The majority of the theories attempt to account for the QSO's as objects at cosmological distances, but some are compatible with the idea that they are objects thrown out of galaxies. Some attempt is made to explain the properties of the radio galaxies as well. In very few, if any, of the theories is the physical mechanism which leads to the release of energy largely in the form of relativistic matter described satisfactorily. If the QSO's are coherent objects ejected from radio galaxies, or indeed objects ejected in galactic explosions in general, the underlying mechanism is obscure.

A fundamental assumption made in nearly all of the hypotheses so far put forward is that matter is present in a highly condensed form. We consider first the theories based on the idea that dense galactic nuclei are present.

Supernova Theories

For several years the group at Livermore, under the direction of Colgate, have been considering the hydrodynamics of the final stages of evolution of a supernova, with their starting point the final stages of nuclear evolution discussed by others (cf. 90). They start with a hot evolved star of mass 10 $M_{\odot}$ which is dense enough to be unstable against gravitational collapse, and follow it as it falls inward (70). A shock is formed, heating results, and nuclear reactions take place. The core falls in rapidly and the outer part more slowly. The energy released in the collapse is emitted largely in the form of neutrinos. These escape if, and until, the outer parts of the star have collapsed to a high enough density so that a significant opacity to the neutrino flux is produced. At this point the neutrinos exert sufficient force to halt the collapse of the outer part of the star, which is ejected. At the same time the inner parts of the star continue to collapse and can form a stable neutron configuration, if the infalling mass is less than the critical mass for a neutron star. With the approximations chosen and using Newtonian gravitational theory, Colgate & White (70) concluded that about 10^{-3} of the total mass energy could be ejected, i.e., about 10^{52} ergs from a 10 $M_{\odot}$ star, while about 2×10^{51} ergs was ejected in the form of relativistic particles. This is more than 100 times the energy for which we have direct evidence of release in a supernova. If correct, this much larger energy release makes the supernova hypothesis for strong radio sources and QSO's more attractive again. It should be remembered that the energy is gravitational in origin.

Colgate & Cameron (69) (see also (56)) first applied the argument to attempt to account for the light variations in QSO's. They suggested that the very large luminosities were produced by the ejected gas heating surrounding interstellar gas. A more ambitious attempt to explain the flux radiated by a cosmologically distant QSO (3C 273 being taken as the prototype) was recently made by Colgate (68), starting with an assumed star density of $\sim 10^{10}/pc^3$. Massive stars (50 $M_\odot$) will be formed by inelastic collisions between the original stars. These evolve to the supernova stage in times $\sim 10^6$ years and supernova explosions occur at a rate $\sim$ 3 per year. The kinetic energy ejected from the supernovae then heats the gas remaining from previous explosions, and it is this excited gas which gives rise to the high luminosity with a variable component. The radio emission is supposed to arise from the material at very high kinetic energy (0.1 c^2/gm). This passes through the bulk of the gas cloud with little energy loss but at the boundary of the dense cloud a counter-streaming plasma oscillation instability occurs in which ions and electrons share kinetic energy. The radio emission is then supposed to arise from electrostatic bremsstrahlung and this is scattered from coherent plasma oscillations giving the spectral characteristics of 3C 273B. It is claimed that this model avoids the difficulties associated with synchrotron emission models. A still higher-energy component of gas ejected from supernovae at relativistic speeds is then invoked to give rise to the radio source 3C 273A, and such components will also be required for any QSO's which have extended radio sources. Although many of the details of this model are not easily understood, the whole concept is highly ingenious. The underlying model involving many supernovae may also be considered for the strong radio galaxies.

Aizu et al. (3) considered a possible mechanism of explosion in a galactic nucleus which contains a high density of stars together with gas. They supposed that the gas may speed up the evolution of the stars, and induce collective explosions of stars. They call this a "pile theory" but have not worked out the consequences in detail.

Stellar Collisions

Given a very high star density in a galactic center, the stars interact more and more rapidly, through inelastic collisions. The velocity dispersion of the stars gets larger as the cluster shrinks, the violence of the star collisions increases, and at high enough energy the stars will completely disrupt. Throughout this process some stars will be ejected from the cluster at higher and higher velocities. These stages have been considered in some detail recently by Spitzer & Saslaw (212), following earlier work summarized elsewhere. Very high star densities $\sim 10^{11}$ stars/pc^3 may be required in such a model. If the collision velocities are $\sim 10^4$ km/sec, the kinetic energy available is some 10^{51} erg/$M_\odot$. This class of model, however, suggests that the violent phase in which most of the energy is released (the QSO phase) will be very short, about $10^9 - 10^{10}$ seconds.

In such violent star collisions the major part of the kinetic energy will be dissipated by radiation processes and some mass will be ejected from the cluster. However, most of the matter will fall back together and give rise to a massive cloud, with a small net angular momentum. This is not perhaps the only way in which a very condensed object can be produced. However, it is the final evolutionary phase of a dense galactic nucleus of stars. How long it takes to evolve to this state depends on the initial density assumed. If this is low, comparable to the densities seen in nearby galaxies, the total time involved may be much longer than the Hubble time.

Massive Super-Stars

The previous discussion leads naturally to the investigations of Hoyle & Fowler (111,112 (see also (113)), who first considered the problem of the release of gravitational energy in the collapse of a super-star. The basic idea of Hoyle & Fowler is well known; it is that in the gravitational collapse of a massive object a small but significant fraction of the rest mass energy may be released. Close to the Schwarzschild radius it is very difficult for energy to be emitted in a spherically symmetrical collapse, unless it is supposed that the theory of general relativity is modified in this extreme condition. The role of rotation in the relativistic regime is unclear, though it has been suggested (226) that expulsion of matter can occur in extreme configurations.

Modification of the theory of relativity has been attempted by Hoyle & Narlikar (114) who introduced a field of negative energy which they had considered in their cosmological investigations. This halts gravitational collapse, and the object might carry out radial oscillations which would take it for some part of the time outside the Schwarzschild radius and in this phase energy could be emitted.

In gravitational collapse of a massive object it is not clear in what form the energy will be emitted. The most efficient process would be if it was in the form of high energy particles, since many arguments suggest that processes converting energy from any other form to high energy particles are inefficient.

If the QSO's are local objects ejected from galaxies, then the energy must be emitted in coherent lumps with high density cores. These would be most likely to be produced in a process of fragmentation, perhaps due to rotation in the final collapse phases. Obviously a proper theoretical treatment of such ideas will be required, if the local hypothesis for QSO's is to be pursued.

While the gravitational collapse theory for the large energy of radio sources remains a popular one despite the difficulties, Fowler (88,89), following his earlier work, has also attempted to account for the optical properties of the QSO's by considering the early collapse phases of a massive object, in which normal hydrogen burning gives a luminosity of 2×10^{46} erg/sec for a mass of 10^{8} $M_{\odot}$. Fowler had estimated that the total thermonuclear energy available in a massive star would enable it to radiate for $\sim 10^{6}$ years, but the general relativistic instability of a non-rotating star means that it cannot be stable for this long but must undergo free-fall collapse (89,57, 58, 59). However, it has now been shown (89, 173) that a small amount of rotation is able to stabilize the massive star against gravitational collapse for a limited period, and that turbulent or magnetic forces will also be able to stabilize the star as long as it contains nuclear energy sources. Thus a massive star may be able to exist for $\sim 10^{6}$ years in its thermonuclear burning phase, provided that its mass does not exceed $10^{8} - 10^{9}$ $M_{\odot}$.

It should be remembered that for any QSO's in which very extended radio sources are seen, at least two massive objects are required. One must have formed, evolved to the gravitational collapse stage and emitted enough high energy particles to give rise to the extended source, while a second must currently be passing through its thermonuclear phase to produce the quasi-stellar component. To explain the strong radio galaxies by this mechanism the massive object must have evolved and collapsed to give rise to the extended radio source.

The Role of Magnetic Fields in Massive Objects

Little attention has been paid until recently to the problem of the magnetic fields which are an integral part of the phenomenon to be explained. It has commonly been assumed that the conditions which give minimum total energy requirements for synchrotron emission hold, i.e. homogeneous uniform fields of $10^{-4} - 10^{-5}$ gauss. However, (see discussion by Woltjer (231)) it is difficult for magnetic fields as strong as this to have been either ejected in the relativistic plasma cloud in the central explosion, or amplified from a much weaker intergalactic field by the explosion. If the fields are smaller, then the total energy requirement of the source is greater than the minimum total energy, and most of the energy is in the relativistic particles.

In the highly condensed QSO's there are strong arguments for believing that a non-homogeneous magnetic field is present, and also there is no reason to believe that the equipartition condition is fulfilled. In order to avoid many difficulties, particularly if the QSO's are at cosmological distances, it may be necessary to invoke very strong magnetic fields $\geq$ 100 gauss in some regions.

If the relativistic particles gain energy by a conventional acceleration mechanism, the magnetic field will play an important role in energy transfer, and its configuration is one of the main factors determining the synchrotron radiating properties of the source. A number of authors (92, 91, 161, 122, 163, 164, 219, 220) have explored some possibilities following the hypothesis that gravitational energy released in the condensation and collapse of a massive object is converted to magnetic energy and through it to the relativistic particles.

Both Piddington & Sturrock discussed qualitatively the condensation of a mass of galactic size out of the intergalactic medium. Piddington (163) considered the condensation of galaxies from gas clouds with frozen-in magnetic fields and argued that when the rotational ($\vec{\omega}$) and magnetic field ($\vec{B}$) vectors are orthogonal, radio galaxies result. Stars form while the uncondensed gas continues to shrink, giving rise to a condensed mass, while if star formation is inhibited by some process the whole galactic mass will shrink to "nuclear" dimensions and a QSO will result.

Sturrock's argument (220) is based on a model of his and Coppi's for solar flares which must be scaled up by an enormous factor. A galaxoid or protogalaxy, a compact elliptical galaxy, a galactic nucleus, or a QSO, is condensed from the intergalactic gas so that it maintains a connection with the intergalactic magnetic field and accretes matter from it. The intergalactic material is supposed to be fully ionized and the magnetic field has an hour-glass configuration through the object; accreted matter will be "funnelled" into the condensed object. The angular momentum problem is briefly mentioned.

The situation is reached in which the galaxoid or QSO is highly condensed and contains magnetic energy that supports it against gravitational collapse, which condition implies that $\Phi \approx 10^{-3}$ M where Φ is the flux in gauss cm^2 and M is the mass in grams of the condensed object. If now the values of Φ for the extended radio sources calculated by Maltby et al. (139) are inserted, masses of the order discussed by Hoyle & Fowler in the gravitational collapse hypothesis are obtained. However, one must remember that in the calculations of Maltby et al. the equipartition condition giving the minimum total energy in particles plus magnetic field was assumed, and there is no physical basis for this result as we have stressed earlier, and then Hoyle & Fowler chose masses in the range such that the release of rest mass energy would provide energy equal to the minimum equipartition values. Thus it is not surprising that Sturrock recovered the initial condition of Hoyle & Fowler.

Sturrock then argues that energy release from the QSO will be the tearing mode instability in the region of the sheet pinch which, in his assumed magnetic field configuration, is perpendicular to the axis of the hour glass. This instability will give rise to ejection of a pocket of magnetic field and high-energy particles which comprise the jets seen in QSO's and radio galaxies.

Such a jet will eventually divide into two clouds which will be the double radio source. The main interest in this model lies in the plasma instability mechanism. Given the condensed object together with the necessary magnetic field configuration the model is attractive.

Piddington (163,164) paid more attention to the problems of rotation in a contracting cloud. When $\vec{\omega}$ and $\vec{B}$ are orthogonal rotational energy is converted to magnetic energy so that a continuing and steady collapse can occur. The object eventually reaches a spherical state followed by explosions along the $\pm\omega$ axis. The particles are accelerated in a neutral sheet at the expense of magnetic energy in a process bearing some resemblance to that of Sturrock. Piddington has argued that the hour-glass magnetic field model is one that gives rise to a normal spiral galaxy ($\vec{\omega}$ parallel to $\vec{B}$) and thus reaches quite a different conclusion from Sturrock in this respect. The difference lies in Sturrock's neglect of the effect of rotation in his model.

While flare models of this type are attractive and promising, they require initial conditions that cannot be deduced from observation nor unambiguously derived by theoretical argument.

Ginzburg & Ozernoy (92) started from the idea that QSO's and strong radio galaxies get their energy from the gravitational collapse of a massive super-star. A very large spherically symmetric mass condenses into a small volume; they consider the effect of further collapse on the magnetic dipole moment which is trapped within the object. The magnetic energy is assumed to be small compared with the gravitational energy of the initial star. As the star collapses, the magnetic field grows, reaching enormous values in the star's interior. In the lower density atmosphere surrounding the star, conditions may develop so that a current-carrying shell may become detached. Thus the collapsing magnetic star may develop very powerful "radiation belts" within a magnetosphere, and it is argued that it is these regions which give rise to the flux of optical and radio emission in quasi-stellar objects. Ozernoy (161) developed a model of a "magnetoid" - a quasi-stationary configuration in stable rotation along the lines of force of a toroidal magnetic field; such a model can explain some of the variable features of QSO's, particularly if they are quasi-periodic. While Ginzburg & Ozernoy stress that the development and structure of this model involve many unsolved complex problems, the model has some attractive features. It may be able to account for the very strong magnetic fields that are required to avoid some of the difficulties discussed earlier. It is not clear, however, how most of the gravitational energy is to be transformed to the high energy particles which radiate in this field.

The classes of theory outlined above involve either the evolution and shrinkage to high densities of a galactic nucleus of stars, or the formation of a dense gas cloud by condensation in the intergalactic medium, an idea first proposed by Field (84) who suggested that QSO's were galaxies in the process of formation. But the formation of a dense object is not well understood. McCrea (143) suggested that the problem of the formation of condensations may be man-made and that there is no evidence that nature poses such problems. The dense phase might be either a remnant of the very early evolution of the universe in which all the mass energy was contained in a very small volume, or else it might be supposed that matter is continuously created in conditions of high density. These ideas tie the QSO's and the radio galaxies directly to cosmological theories. Various models are described next.

Theories Using the Concept that Massive Objects Have a Cosmological Origin

Proposals along this line were made by McCrea (143), Hoyle & Narlikar (115), Stothers (215), Novikov (154), and Ne'eman (151).

McCrea considered a modification of the steady state theory in which matter is created only in the presence of already existing matter. Thus all matter is contained in galaxies, and continuous creation simply increases the galactic mass. Occasionally a galaxy may eject a fragment, which is then the embryo out of which a new galaxy is grown. Such embryos are closely related to the quasi-stellar objects, and the phenomena of outburst and ejection from galaxies to produce radio sources are to be associated with the creation and ejection process. Such a model could explain the QSO's if they have a local origin.

A rather similar proposal has been made by Hoyle & Narlikar. They show that the growth in "pockets" of creation is likely to be an unstable process, since the growth of a mass of infinity takes only twice the time for the mass to double itself. Such a runaway process will be prevented by a fragmentation of the growing mass, and each fragment will serve as an individual pocket of creation - the embryo in McCrea's formulation.

Stothers, on the other hand, argued that matter is created between clusters of galaxies just because matter is lacking here, and the QSO's (which may not occur in clusters) are the manifestation of this creation. However, for a variety of reasons the McCrea-Hoyle-Narlikar hypothesis is more attractive.

If the universe is evolutionary, then the superdense objects could be inhomogeneities remaining in the general expansion of the universe, and again the problem of forming condensations out of a diffuse intergalactic background is by-passed. Ne'eman proposed that the QSO's, which he supposed are cosmological objects, are in an expanding state which have lain near the singular state for some 10^{10} years. Thus in its own coordinate system the object is behaving as a miniature expanding universe. Extremely large energies must have accumulated from strong interactions in the superdense state with no outlet for the decay of various mesons. Having attained a lower density in the slow expansion these mesons and hence high energy particles may be released.

The argument of Novikov is rather similar to this though he suggested that energy is released when shells of matter moving outward in the expansion collide with shells which have been ejected earlier, or with matter falling onto the object from outside (154).

In this whole class of theory conventional acceleration mechanisms for high energy particles are not invoked, and the high energy particles are directly injected. The ideas contained in these theories were foreshadowed in the early papers of Ambartsumian (7).

A problem not covered in these theories is associated with the apparently normal composition of the gas cloud giving the line radiation in the QSO's. It must be supposed either that extensive nucleosynthesis has gone on in the evolution of these objects leading to normal composition - an unlikely situation - or else that the object has managed to accrete material with normal composition.

Classes of theory involving fundamental particles will be outlined next.

Quarks as Energy Sources in Massive Objects with a Cosmological Origin

If quarks exist, they might form the major constituent of the universe in a stage in which matter has not evolved. Thus bare quarks might have predominated early in an evolving universe, while in a steady state universe matter might be continuously created in the form of quarks. The situation in an evolving universe has been discussed by Zeldovich et al. (236) and by Saslaw (189). The former discussed a situation in which the quarks burned out in the first few microseconds of the expansion, and Saslaw considered that cosmological information might be obtained by considering the role of the quarks in this very short epoch.

If quarks are of importance in these cosmologically dense configurations and if massive objects containing bare quarks are left behind in the initial expansion, or are present in newly created material, then as the objects evolve they can give rise to the major constituents of the radio sources and QSO's. The first mention of this possibility was made by Pacini (162); it is discussed further in (50).

Matter - Antimatter Annihilation

This mechanism was suggested ten years ago for radio galaxies (47, 53), but dropped because of the difficulty in understanding how matter and antimatter could be created or evolve and remain separated, and then later be brought into interaction in isolated events.

Alfvén & Klein (5) proposed a model universe in which matter and antimatter enter in a symmetric way. Alfvén (4) developed the concept of an "ambiplasma" which contains both kinds of matter and he showed that a mechanism of separation involving the magnetic field was possible. If one accepts this type of cosmology then the difficulties just mentioned can be removed. However, this type of cosmological model based on the old theoretical model of Charlier is probably not compatible with present views. Setting aside this objection for the moment we consider the consequences of the annihilation proposal further. Ekspong et al. (80) attempted to account for the radio spectra of some QSO's and radio galaxies using this idea. They calculated the electron positron spectrum through the decays of the π and μ mesons produced in $p\bar{p}$ annihilation, calculated the resulting synchrotron spectra, and compared these with observations of 3C 48, 3C 147, 3C 286, CTA 102, and the radio galaxies Cygnus A and 3C 295. The calculated spectra are curved and show a tendency to flatten at low frequencies. As discussed earlier the generally accepted reason for this flattening is that it is an approach to synchrotron self-absorption in sources containing very small components. An objection to this theory is that to give radiation in the observed frequency range large magnetic fields are required, $\sim 10^{-2}$ gauss. For the extended sources which include 3C 147, Cygnus A, and 3C 295, the minimum total energy condition gives magnetic fields in the range 10^{-4} - 10^{-5} gauss. If the magnetic field is much larger than this, as it has to be in this theory using very low energy electrons, then there is a strong departure from the minimum total energy condition. This in itself does not mean that it is not a plausible hypothesis, but it does mean that the total energy in particles and magnetic field is many orders of magnitude greater than the minimum, and most of it is in the magnetic field. Thus one is left with the difficulty of explaining the origin of an enormous amount of energy in the magnetic field which cannot arise from annihilation. This model is therefore unsatisfactory.

Gravitational Focussing

Barnothy (20,21,22) suggested that the very high luminosities of the QSO's, assumed to be at cosmological distances, are due to amplification by gravitational focussing by a large concentration of mass lying very close to the light path between the QSO and the observer. The focussing objects must be dark; otherwise their own radiation would swamp the flux which is to be focussed. Moreover, they must occur quite frequently in space in order that the chance of this effect occurring is to be non-negligible. Both of these conditions are inherently implausible. In addition it is necessary still to postulate the existence of objects with the spectral properties of the QSO's, since this effect only increases the apparent luminosities and does not change the spectra. Therefore Barnothy argued that the QSO's are the nuclei of very distant Seyfert galaxies. However, while the latter bear some spectral resemblance to the QSO's, the two classes of objects are clearly distinguishable. These are strong arguments against the proposal.

CONCLUSION

The task of writing a review on a subject changing as rapidly as this one is somewhat difficult; new observations are perhaps being made at this moment which will make the review already out of date, and likewise new theoretical ideas are perhaps being formulated at the same time.

In the observational sections, I have devoted more space to the optical than the radio data, and this is merely a reflection of where my own work lies.

In conclusion, I would like to express my gratitude to the many colleagues who have sent preprints ahead of publication, and particularly to Geoffrey Burbidge, who did much of the assembling of data and most of the writing of the book (50) from which this review is a condensed account.

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Table I

LIST OF QUASI-STELLAR OBJECTS

OBJECT	α(1950)	δ(1950)	m_V	z	B-V	U-B
PHL 658	0^h 03^m $25^s.4$ (radio)	$+15^\circ$ 53'10"	16.40	0.450	+0.11	-0.70
3C 2	0 03 48.70	-00 21 06.6	19.35	1.037	+0.79	-0.96
3C 9	0 17 49.83	+15 24 16.5	18.21	2.012	+0.23	-0.76
MSH 00-29	0 22 01	-29 45.5	(20)			
PHL 6638	0 44 35.3 (radio)	-07 22.0	17.72		+0.18	-0.69
PHL 923	0 56 31.7	-00 09 16	17.33	0.717	+0.20	-0.70
PHL 938	0 58.2	+01 56	17.16	1.93	+0.32	-0.88
PKS 0106 + 01	1 06 04	+01 19.0	18.39	2.107	+0.15	-0.70
PKS 0114 + 07	1 14 49.7	+07 26.3	(18)			
3C 39	1 18 27.6	+03 28 19				
PKS 0122-00	1 22 55.5	-00 21 34	(16)	1.070		
3C 43	1 27 15.18	+23 22 52.0	(20.0)			
3C 47	1 33 40.30	+20 42 16.0	18.1	0.425	+0.05	-0.65
3C 48	1 34 49.8	+32 54 20	16.2	0.367	+0.42	-0.58
PHL 1078	1 35 29.1 (radio)	-05 42.1	18.25	0.308	-0.04	-0.81
PHL 1093	1 37 22.9 (radio)	+01 16.3	17.07	0.262	+0.05	-1.02
PHL 3740	1 44 14.9 (radio)	-05 54.2	18.61		+0.09	-0.65
3C 57	1 59 30.4	-11 47 0	16.40		+0.14	-0.73
PHL 1305	2 26 21.6 (radio)	-03 54.3	16.96	2.064	+0.07	-0.82
PHL 1377	2 32 36.4 (radio)	-04 16.9	16.46	1.439	+0.15	-0.89
3C 93	3 40 51.47	+04 48 21.6	18.09		+0.35	-0.50
PKS 0347 + 13	3 47 14.0	+13 10 01	(19)			
MSH 03-19	3 49 9.5	-14 38 07	16.24	0.614	+0.11	-0.65

3C 94	3^h	50^m	$04^s.1$	-07°	19'55"		(17.5)	0.962		
PKS 0403-13	4	03	14.0	-13	16	16	(18)	0.571		
MSH 04-12	4	05	27.4	-12	19	34	(16)			
3C 119	4	29	07.84	+41	32	08.7	(>20.0)			
3C 138	5	18	16.5	+16	35	26	17.9	0.760	+0.23	-0.38 (reddened)
3C 147	5	38	43.5	+49	49	43	16.9	0.545	+0.35	-0.59
PKS 0541-24	5	41	09.5	-24	22.7					
3C 172	6	59	04.5	+25	17	36	(17.2)			
3C 175	7	10	15.3	+11	51	30	(17.5)	0.768		
3C 175.1	7	11	14.3	+14	41	33	(18.0)			
3C 181	7	25	20.36	+14	43	47.2	18.92	1.382	+0.43	-1.02
PKS 0736 + 01	7	36	42.4	+01	43	57	(18)	0.191		
3C 186	7	40	56.67	+38	00	31.9	17.60	1.063	+0.45	-0.71
3C 190	7	58	44.1	+14	23	0	17.46		-0.20	-0.90
3C 191	8	02	3.78	+10	23	58.1	18.4	1.946	+0.25	-0.84
3C 196	8	09	59.4	+48	22	08	17.6	0.872	+0.60	-0.43
PKS 0812 + 02	8	12	47.2	+02	04	11	(17)			
PKS 0825-20	8	25	03.4	-20	16	31	(18)			
4C 37.24	8	27	55.0	+37	52	20	(18.2)	0.914		
3C 204	8	33	18.23	+65	24	05.9	18.21	1.112	+0.55	-0.99
3C 205	8	35	10.6	+58	04	46	(17.8)			
3C 207	8	38	01.7	+13	23	05.4	18.15	0.683	+0.43	-0.42
3C 208	8	50	22.79	+14	03	58.3	17.42	1.110	+0.34	-1.00
PKS 0859-14	8	59	55	-14	03	37	(17.8)	1.327		
4C 22.22	9	01	56.5	+22	31	36	(19.0)			
3C 215	9	03	44.2	+16	58	16	18.27	0.411	+0.21	-0.66
3C 217	9	05	41.0	+38	00	27	18.50		+0.25	-0.86
3C 216	9	06	17.26	+43	05	59.0	18.48		+0.49	-0.60
PKS 0922 + 14	9	22	22.27	+14	57	26.2	17.96	0.895	+0.54	-0.52

4C 39.25	9^h	23^m	$55^s.4$		$+39^\circ$	15'24"	(17.3)	0.699			
3C 230	9	49	25.5		+00	12 57	(17.5)				
3C 232 = Ton 469	9	54	31	(radio)	+32	37	15.78	0.53	+0.10	-0.68
0952 + 18	9	52	11.92		+17	57 46.6	(17.7)	1.471		
PKS 0957 + 00	9	57	43.84		+00	19 50.0	17.57	0.906	+0.47	-0.71
3C 239	10	08	37.5		+46	43 15	(17.5)			
3C 245	10	40	06.11		+12	19 15.1	17.25	1.029	+0.45	-0.83
PKS 1049-09	10	48	59.5		-09	02 12	16.79		+0.06	-0.49
PKS 1040 + 12	10	40	05.9		+12	19.3	(18)			
3C 249.1	11	00	30.56		+77	15 08.1	15.72	0.311	-0.02	-0.77
3C 254	11	11	53.35		+40	53 42.0	17.98	0.734	+0.15	-0.49
PKS 1116 + 12	11	16	20.79		+12	51 06.3	19.25	2.118	+0.14	-0.76
PKS 1127 - 14	11	27	35.6		-14	32 57	16.90	1.187	+0.27	-0.70
3C 261	11	32	16.31		+30	22 1.0	18.24	0.614	+0.24	-0.56
PKS 1136 - 13	11	36	38.6		-13	34 09	(17)			
3C 263	11	37	09.38		+66	04 25.9	16.32	0.652	+0.18	-0.56
PKS 1148 - 00	11	48	10.2		-00	07 15	17.60	1.982	+0.17	-0.97
4C 31.38	11	53	44.4		+31	44 47	(19.4)	1.557		
3C 268.2	11	58	22.5		+31	50 08	18.31		+0.42	-0.20
3C 268.4	12	06	41.7		+43	56 05	18.42	1.400	+0.58	-0.69
PKS 1217 + 02	12	17	38.35		+02	20 20.9	16.53	0.240	+0.02	-0.87
3C 270.1	12	18	04.00		+33	59 50.0	18.61	1.519	+0.19	-0.61
4C 21.35	12	22	23.5		+21	39 27	(18.0)	0.433		
Ton 1530	12	22	57		+22	53	(16.8)	2.051		
3C 273	12	26	33.35		+02	19 42.0	12.8	0.158	+0.21	-0.85
PKS 1229 - 02	12	29	25.9		-02	07 31	16.75		+0.48	-0.66
PKS 1233 - 24	12	32	59.4		-24	55 46	(17)			
PKS 1237 - 10	12	37	07.3		-10	07 04	(18.2)			

3C 275.1	12^h	41^m	$27^s.68$	+16°	39'	18".7	19.00	0.557	+0.23	-0.43
BSO 1	12	46	29	+37	46	25	16.98	1.241	+0.31	-0.78
3C 277.1	12	50	15.31	+56	50	37.0	17.93	0.320	-0.17	-0.78
PKS 1252 + 11	12	52	07.86	+11	57	20.8	16.64	0.871	+0.35	-0.75
3C 279	12	53	35.94	-05	31	08.0	17.8	0.538	+0.26	-0.56
3C 280.1	12	58	14.15	+40	25	15.4	19.44	1.659	-0.13	-0.70
3C 281	13	05	22.52	+06	58	16.4	17.02		+0.13	-0.59
4C 22.38	13	24	29.9	+22	58	22	(18.9)			
PKS 1327 - 21	13	27	23.2	-21	26	34	16.74	0.528	+0.10	-0.54
3C 287	13	28	16.12	+25	24	37.1	17.67	1.055	+0.63	-0.65
3C 286	13	28	49.74	+30	45	59.30	17.30	0.849	+0.22	-0.84
MSH 13-011	13	35	31.34	-06	11	57.4	17.68	0.625	+0.14	-0.66
3C 288.1	13	40	30.4	+60	36	55	18.12	0.961	+0.39	-0.82
PKS 1354 + 19	13	54	42.3	+19	33	41	16.02	0.720	+0.18	-0.55
3C 298	14	16	38.59	+06	41	41.52	16.79	1.439	+0.33	-0.70
4C 20.33	14	22	37.5	+20	13	49	(17.1)	0.871		
MSH 14-121	14	53	12.22	-10	56	39.9	17.37	0.940	+0.44	-0.76
PKS 1454 - 06	14	54	02.7	-06	05	45	18.0	1.249	+0.60	
3C 309.1	14	58	57.6	+71	52	19	16.78	0.904	+0.46	-0.77
PKS 1510 - 08	15	10	08.9	-08	54	48	16.52	0.361	+0.17	-0.74
PKS 1514 + 00	15	14	14.8	+00	26	01	(19)			
3C 323.1	15	45	31.2	+21	01	34	(15.8)	0.264		
MSH 16 + 03	16	03	39.5	+00	07	55	(18.0)			
Ton 256	16	12.0		+26	13		15.91	0.131	+0.57	-0.84
3C 334	16	18	07.40	+17	43	30.5	16.41	0.555	+0.12	-0.79
3C 336	16	22	32.45	+23	52	00.7	17.47	0.927	+0.44	-0.79
3C 345	16	41	17.70	+39	54	11.1	16-17.30	0.595	+0.29	-0.50
3C 351	17	04	03.58	+60	48	29.9	15.28	0.371	+0.13	-0.75
3C 380	18	28	13.38	+48	42	39.3	16.81	0.692	+0.24	-0.59

PKS 2115 - 30	21^h	15^m	$11^s.1$	-30°	31'50"		16.47		+0.49	-0.54
3C 432	21	20	25.64	+16	51	46.0	17.96	1.805	+0.22	-0.79
3C 435	21	26	37.6	+07	19	49	(19.5)			
PKS 2145 + 06	21	45	36.0	+06	43.7		(17.5)			
PKS 2146 - 13	21	46	46.1	-13	18	24	(20)	1.800		
PKS 2154 - 18	21	54	12.5	-18	28.5		(16.5)			
PKS 2216 - 03	22	16	16.3	-03	50	43	(17)	0.901		
3C 446	22	23	11.05	-05	12	17.0	18.39	1.403	+0.44	-0.90
PHL 5200	22	25	50.6	-05	30.6		(18.2)	1.981		
CTA 102	22	30	07.71	+11	28	22.8	17.32	1.037	+0.42	-0.79
3C 454	22	49	07.86	+18	32	46.6	18.40	1.757	+0.12	-0.95
3C 454.3	22	51	29.61	+15	52	53.6	16.10	0.859	+0.47	-0.66
PKS 2251 + 11	22	51	40.5	+11	20.6		(17)			
4C 29.68 = CTD 141	23	25	41.3	+29	20	36	(17.3)	1.012		
PKS 2344 + 09	23	44	04.0	+09	14.0		(17.5)			

Table II

QUASI-STELLAR OBJECTS WITH REDSHIFTS

Object	z	Reference	Object	z	Reference
Ton' 256	0.131	179	PKS 2216-03	0.901	134a
3C 273	0.158	192	3C 309.1	0.904	43, 134a
PKS 0736+01	0.191	134a	PKS 0957+00	0.906	135, 105
PKS 1217+02	0.240	135, 87, 105	4C 37.24	0.914	134a
PHL 1093	0.262	134a	3C 336	0.927	135
3C 323.1	0.264	*	MSH 14-121	0.940	39, 195
PHL 1078	0.308	134a	3C 288.1	0.961	*
3C 249.1	0.311	195, 87, 105	3C 94	0.962	134a
3C 277.1	0.320	195, 105	4C 29.68†	1.012	195, 134a
PKS 1510-08	0.361	43	3C 245	1.029	194, 137
3C 48	0.367	96	CTA 102	1.037	194
3C 351	0.371	137	3C 2	1.037	134a
3C 215	0.411	135	3C 287	1.055	194
3C 47	0.425	196	3C 186	1.063	135
4C 21.35	0.433	43, 134a	PKS 0122-00	1.070	134a
PHL 658	0.450	134a	3C 208	1.110	41, 195
PKS 1327-21	0.528	43	3C 204	1.112	195
3C 232	0.534	*	PKS 1127-14	1.187	43
3C 279	0.538	137, 46	BSO 1	1.241	179
3C 147	0.545	196	PKS 1454-06	1.249	43
3C 334	0.555	137, 40	PKS 0859-14	1.327	43
3C 275.1	0.557	135	3C 181	1.382	195
PKS 0403-13	0.571	134a	3C 268.4	1.400	*
3C 345	0.595	137, 40	3C 446	1.403	40, 195

MSH 03-19	0.614	195	PHL 1377	1.439	105
3C 261	0.614	135, 43	3C 298	1.439	135
MSH 13-011	0.625	43	0952+18	1.471	₮
3C 263	0.652	87	3C 270.1	1.519	195
3C 207	0.683	134a	4C 21.38	1.557	43
3C 380	0.692	179, 40	3C 280.1	1.659	135
4C 29.25	0.699	135, 43	3C 454	1.757	195
PHL 923	0.717	134a	PKS 2146-13	1.800	134a
PKS 1354+19	0.720	43	3C 432	1.805	195
3C 254	0.734	194	PHL 938	1.93	126
3C 138	0.760	135, 43	3C 191	1.946	45, 214
3C 175	0.768	134a	PHL 5200	1.981	134a
3C 286	0.849	137	PKS 1148-00	1.982	43
3C 454.3	0.859	134a	3C 9	2.012	194
PKS 1252+11	0.871	137, 195, 105	Ton 1530	2.051	105
4C 20.33	0.871	135	PHL 1305	2.064	134a
3C 196	0.871	135	PKS 0106+01	2.107	41
PKS 0922+14	0.895	135, 105	PKS 1116+12	2.118	195, 136

* M. Schmidt, in preparation

† 4C 29.68 = CTD 141

₮ C. Hazard, M. Schmidt, E. M. Burbidge, in preparation